The Pennsylvania State University

The Graduate School

Department of Civil Engineering

CHARACTERIZATION OF CONSTRUCTION EQUIPMENT SOUNDS AND USES IN THE FIELD

A Thesis in

Civil Engineering

by

Joseph G. Orlowsky

Submitted in Partial Fulfillment
of the Requirements
for the Degree of

Master of Science

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ABSTRACT

Automated data acquisition and interpretation is an area of construction research currently being developed to improve the level of productivity and the quality of decision making as it relates to project control. This thesis discusses the applicability of acoustic signal analysis as a valid remote sensory technology for extraction of data from a construction environment. The scope of this research has been limited to the study of equipment intensive operations. In demonstrating the applicability of acoustic signal analysis, key measurable characteristics of sound are first discussed, followed by an overview of the equipment used for data collection and analysis. Detailed information is then presented describing specific signal analysis modes utilized to visually identify acoustic features representative of specific types of equipment. Utilizing two types of analysis - spectral and spectrographic - results of six types of construction equipment are then presented to demonstrate qualitatively, how, through pattern recognition specific features can be used to distinguish one type of equipment from another. Further results are presented to prove that loaded hauling units can be distinguished from empty units based upon their acoustic signature. Based upon conclusions obtained from actual results of samples, potential applications for acoustic sensory technology relevant to the construction environment are provided.

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CHAPTER 1

INTRODUCTION

Background

In the competitive business world of the 1990's, **Information** has become a valuable commodity, capable of affecting both the profitability and survival of business organizations. Acknowledging this need, many segments of industry have taken advantage of advances in computer technology to automate and enhance information gathering systems - particularly in the area of production control.

The construction industry, however, still relies almost entirely on manual data collection techniques as a means of information gathering for project control. While the use of physical observation offers advantages as a means of information gathering (particularly due to human resourcefulness and decision making abilities), such methods are not efficient for many repetitive construction activities. For most applications, manual data collection is costly, subject to error due to differences in human interpretation, and slow with respect to processing the results.

Because of the noted inefficiencies with respect to manual data collection, many contractors refuse to quantitatively track productivity at all. Instead they rely upon their instinct and ballpark estimates of progress from which to base management decisions. Such procedures are often ineffective from a project control standpoint and are one of the root causes of declining cost effectiveness in the construction industry.

Automated data collection methods, on the other hand, can offer numerous advantages over manual collection in a variety of construction applications. Unfortunately, many of the advances made in the area of industrial production control have not been applied to construction operations, largely due to the fact that construction work is field-oriented, subject to frequent reconfiguration of assembly processes, and performed under a variety of environmental conditions.

Despite the obstacles associated with application of automated information gathering, construction researchers at several universities recognized the potential value of such systems in terms of improved productivity and cost effectiveness. Accordingly, in the mid 1980's researchers at Stanford University, The Pennsylvania State University, and University of New South Wales (Australia) began working independently on the conceptual development of automated data acquisition systems tailored for construction applications [Bandyopadyhay 1987, O'Brien 1984 et al., Paulson 1985]. Sensory systems considered to date for data collection include: video pattern recognition, thermography, vibrational energy measurement, and passive acoustic measurement.

Although these data acquisition systems are still in the conceptual stage, the advantages of such systems are obvious. First, the system would provide a systematic, reliable means of data collection, thus eliminating potential error arising from observer boredom or erroneous interpretation of complex operations. Second, such a system could capture and process information much more efficiently than could be

done manually. Third, they would offer considerable long-term cost savings over manual methods, considering the fact that manpower normally directed toward data collection could be directed elsewhere.

Problem Statement

Current information gathering techniques used in construction are labor intensive, time consuming, and subject to error. Development of an automated data acquisition system capable of capturing project information in a systematic, reliable manner offers the potential to greatly improve the quality of decision making and overall cost effectiveness of construction projects.

Objectives of Study

The objective of this research is to demonstrate in qualitative terms that acoustics sensory technology can be used as an effective information gathering tool in a variety of construction applications. Three specific applications are proposed in this paper: productivity data collection, security, and traffic control.

Scope

The scope of this research was limited to the study of six types of construction equipment - three types of hauling units, and three types of support equipment commonly present on hauling operations:

Hauling Units

Cat 627E Scrapers

Euclid 50 Ton off road dump trucks

Euclid 75 ton off-road dump trucks

Support Equipment

CAT D8N bulldozer

Mack 6200 gallon water truck

Ford F-150 pick-up truck

Value of Research

Conceptually, automated data acquisition systems offer a potentially powerful information tool for the construction manager. However, a workable system is still under development, requiring numerous developmental steps prior to implementation. The research performed under this thesis attempts to demonstrate the feasibility acoustic applications as a sensory technology for such systems.

Methodology

To satisfy the objectives of this research, the following tasks were performed:

1. Literature Review. An initial research step, a literature investigation, was conducted of the topics pertaining to automated real-time data acquisition systems and the applied use of acoustic sensory technology in construction. Limited informative literature was found. One paper prepared by Professor O'Brien from the University of

New South Wales discussed studies conducted on the use of acoustic sensing to determine load counts on a tunnel mucking operation [O'Brian,1985]. The paper, however, did not elaborate on the data collection equipment used or analysis procedures applied. A second paper was also located pertaining to acoustic sensing for military intelligence gathering [Acoustic Applications, 1989]. Aside from those sources, limited background material was found.

2. Familiarization of Acoustics and Signal Analysis Equipment. To adequately perform the research, a significant amount of research time was initially devoted to the development of a working knowledge of the basic principles of acoustics, sound transmission, and use of a digital signal analyzer machine.

3. Data Collection. Upon completing background search and familiarization phases of the research, acoustic signals of hauling units and related support equipment were recorded under field conditions at four job sites within a 100 mile radius of State College, Pa. The hauling operations were recorded on a conventional cassette using a portable camcorder and VHS video cassette tapes. Acoustic samples of each type of equipment were recorded under both loaded and unloaded conditions.

4. Data Analysis. Utilizing a Kay model 5500 Digital Signal Processor (DSP), acoustical signals were analyzed to identify key acoustic features capable of characterizing each type of equipment and load status. Two analysis formats were used to accomplish this objective - spectral and spectrographic analysis. From these two analysis

formats, the following characteristics were used as criteria for identification of signal sources:

- upper frequency level of acoustic profile
- frequency with greatest sound power level
- distinctive power spikes in the acoustic profile
- ranges in the acoustic profile with zero energy
- presence of distinctive harmonic features and frequency ranges over which they occur

Utilizing the above criteria, key features relevant to each type of equipment were qualitatively identified.

5. Applications. Utilizing the concepts of acoustic identification presented under step four, three scenarios are presented demonstrating how acoustic sensory technology can be adapted for construction applications.

Organization of the Report

This report is organized into four sections. The first section provides an overview of pertinent acoustic properties studied in the course of the research, followed by a discussion of the signal analysis equipment used and types of analyses employed. The second section addresses how field samples were collected for purposes of this study. The third section illustrates in qualitative terms how acoustic features can be used to identify equipment sources and load status (if a hauling unit). The last section presents three viable applications for passive acoustic sensory technology in the construction environment.

CHAPTER 2

KEY ACOUSTIC PRINCIPLES AND EQUIPMENT APPLIED DURING RESEARCH

Overview

This chapter provides an overview of acoustic principles pertinent to the research, together with a discussion of analysis capabilities of the digital signal processor (DSP). The purpose here is to lay the groundwork for future chapters which will demonstrate how acoustic traits may be used to distinguish among equipment, and address the potential uses of acoustic sensing technology for construction applications.

The chapter is divided into two parts. The first part addresses characteristics of sound and sound transmission; the second part addresses types of signal analyses used to identify acoustic traits of samples collected.

Principles of Sound

By definition, sound is the propagation of mechanical energy from a source by means of longitudinal pressure waves through an elastic medium (usually air). Transmission of sound results when the vibrating source collides with and displaces adjacent air molecules; these molecules, in turn, "bump" adjacent molecules resulting in the transfer of energy outward.

This energy transfer in a compressible medium results in a sound wave consisting of two phases: compression and rarefaction. Compression results when the molecules are forced together, resulting in minor pressure increases. Rarefaction results when the molecules are pulled apart as they attempt to return to their initial state of energy. Minor instantaneous pressure decreases are associated with this phase of the wave [Michael 1977, Peterson 1963, Kinsler 1982]. One sequence of compression and rarefaction together form a wave cycle. This is shown in Figure 2.1.

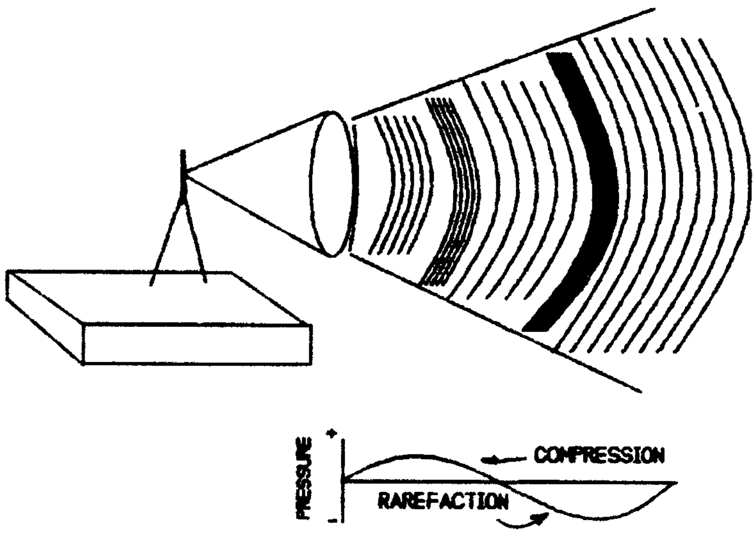


Figure 2.1: Cycle of a Sound Wave and Components

Along with the pressure changes, a finite level of thermal conductivity is also generated as the acoustic wave propagates through air, causing small amounts of energy to dissipate over time and distance due to the collision of molecules. The level of thermal flux varies with temperature of the medium and the velocity of molecules in it. Except in extreme cases, these thermodynamic losses may be considered negligible.

Cycle time of the wave together with the associated incremental pressure changes represent two significant physical characteristics which allow sound to be characterized - frequency and power.

Frequency

Defined as the number of complete pressure variations (set of peaks and compressions) per second of a sound wave, frequency is measured in cycles per second or hertz (HZ). The higher the frequency, the higher the "pitch" appears to the human ear. Hearing, however, is limited to a specific range of frequency, generally from 10 hz to 8000 hz. Sound frequencies above and below this range are classified as ultrasonic and infrasonic, respectively. For purposes of this research, all ranges were investigated.

Sound can consist of a single frequency (a pure tone), or a combination of frequencies (complex tone). Most sounds experienced in the environment are complex tones - a combination of many separate pure tones which exist simultaneously and vary in sound power level. Through the analysis capabilities of a digital signal

processor, it is possible to analyze the distribution of sound power as a function of frequency over a broad range of frequencies. As will be demonstrated later, this relationship between power and frequency provides a primary means of classifying and distinguishing sounds of different equipment.

Power

The intensity of a sound is directly related to the amplitude or sound pressure of the wave. The greater the level of energy emitted from the source, the greater will be the level of compression and associated pressure variations in the medium. Figure 2.2 illustrates this point.

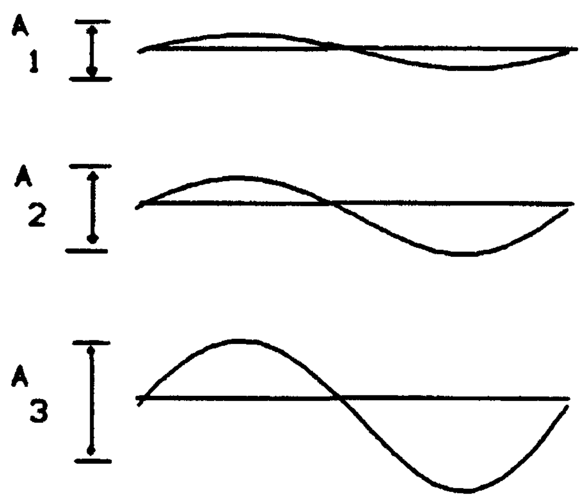


Figure 2.2: Sound Waves of Same Frequency but Different Intensity

Pressure variations associated with sound transmission are relatively small in comparison to atmospheric pressure, usually microbars in comparison to one bar for standard atmosphere. The order of magnitude of sound pressure variations however can vary greatly, from 0.0002 microbars to 200 microbars. Because of this wide domain, sound pressure level (SPL) is commonly measured along a logarithmic scale (base 10) in which the pressure is compared against a reference level of 0.002 microbars - the lowest threshold at which a sound can be perceived. This scale is commonly referred to as the decibel scale. Decibel level of a sound is determined according to the following equation:

$$SPL = 20 \log_{10} (Po/0.002 \text{ microbars}) \text{ db}$$

Where Po = sound pressure recorded at sensor (in microbars)

It is important to note that because decibels are a logarithmic scale, doubling the sound pressure does not result in a decibel rating twice the original value; rather it represents an increase of 6 decibels. This fact is important to remember when comparing decibel levels of two sounds.

Directly related to sound pressure is sound power level (PWL). The sound power level is defined as the acoustic power radiated through a 1 cm^2 area normal to the sound wave over a one second period. Like sound pressure, the PWL is measured using the logarithmic decibel scale, and power is compared against a reference power level. The reference power level commonly used is 10^{-12} watts. Accordingly, the PWL can be determined as follows:

$$PWL = 10 \log W/10^{-12}$$

where W = acoustic power in watts

The meaning and derivation of sound power level is important to understand as the digital signal processors use sound power level as the measurement characteristic in all analysis formats.

Harmonics

As previously presented, most sounds experienced in the environment consist of numerous component frequencies. Among these component frequencies, tones of elevated energy may exist at frequencies which are multiples of another lower component tone. The lowest tone of this group is called the fundamental tone. Additional reverberant tones (described as overtones) may occur at the following frequencies:

$$\text{Overtone Frequency}_{(i)} = (\text{Fundamental Frequency}) * 2^{i}$$

where i = overtone number

This principle is best illustrated in Figure 2.3. In this example, 220 hz represents the fundamental tone of the harmonic group. The second tone, (440 hz) reverberates at exactly twice the speed of the fundamental tone, and is described as the first overtone. The next tone (880 hz) reverberates at exactly four times the speed of the

fundamental, and the last (1760 hz) reverberates at eight times the fundamental tone. Together these first two tones represent the second and third overtone.

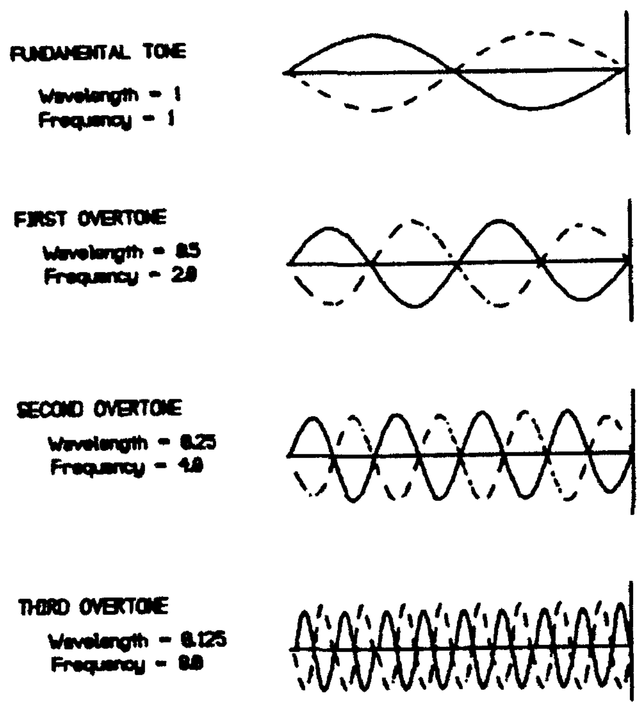
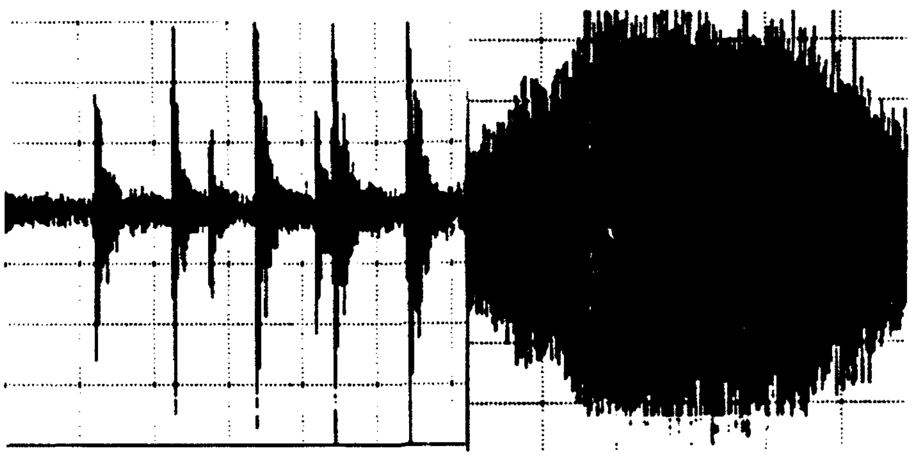


Figure 2.3: Concept of Harmonic Frequencies

While the above example is hypothetical, it conveys the concept of harmonic tones. However, that multiple harmonic groups are likely to be present in construction sounds experienced in the field. As will be demonstrated later, the presence of specific harmonic patterns serve as key identifying features which can be used to determine the source of a sound.

Waveform

The last sound characteristic to be addressed is waveform. Two types of unprocessed waveforms are possible: impact and steady-state. The impact waveform is a short pulse with high initial intensity and rapid decay; indicative of instantaneous nonrepeating action. In contrast, the steady state waveform is relatively stable in terms of amplitude over time, and is indicative of a reciprocating action such as machinery. A comparison of the two type waveforms is shown below in Figure 2.4.



IMPACT WAVEFORM: HAMMERING STEADY-STATE WAVEFORM: PASSING VEHICLE

Figure 2.4: Impact vs Steady-State Waveforms.

While the classification of sound according to waveform seems almost too elementary to be meaningful, it in fact is a powerful tool which facilitates " weeding out" a large volume of transient sounds which are not representative machinery (ie. construction equipment). By eliminating as many impact type signals as possible

sources of construction equipment, in-depth signal analyses can focus on a small sampling of sounds demonstrating general characteristics of construction equipment. Together, these four characteristics - frequency, power, harmonics,and waveform - represent the framework of acoustic features from which signal analysis can be performed.

The next section provides an overview of the signal analysis equipment used and explains the analysis formats employed.

Digital Signal Processor

All signal analyses performed during the course of the research was completed using a Kay model 5500 DSP. The DSP is a multi-functional signal analysis work station presently being used for all types of acoustic research. The system is capable of analyzing any signal in the frequency range of 0-32 khz using one of five analysis modes. Analysis formats include: spectrograph, waveform, power spectrum, amplitude, and waterfall display.

Digitization and processing of the signals was accomplished using an FFT analyzer, enabling quick and versatile processing of input signals. While a complete explanation of FFT analysis process is beyond the scope of this paper, a simplified explanation follows. Under the concept of a FFT Analysis, a steady stream of information (sound) is divided into blocks of information (by frequency) and analyzed separately. After each block of information is processed, the output from each is re-assembled in the same order as the original, forming a composite output signal. The

more blocks of information that the signal is broken into, the greater will be the level of precision or resolution of the analyzed signal. The number of blocks of information over which the signal is divided is commonly referred to as "transform size." Eleven levels of "resolution" or transform sizes were available for analysis of signals using the Kay DSP. Table 2.1 summarizes the degree of resolution in terms of hertz associated with each transform size. For purposes of this study, the highest resolution possible (1024 point transform) was used for all analysis modes

Table 2.1: FFT Sizes and Resultant Frequency Resolution

All Values in Hertz

TRANSFORM SIZE	INPUT FREQUENCY RANGE 250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	8 kHz	16 kHz	32 kHz
50	18.75	37.50	75.00	150.00	300.00	600	1200	2400
75	14.06	28.13	56.25	112.50	225.00	450	900	1800
100	9.38	18.75	37.50	75.00	150.00	300	600	1200
125	7.31	14.63	29.25	58.50	117.00	234	468	936
200	4.69	9.38	18.75	37.50	75.00	150	300	600
256	3.66	7.31	14.63	29.25	58.50	117	234	468
512	1.84	3.69	7.38	14.75	29.50	59	118	236
600	1.56	3.13	6.25	12.50	25.00	50	100	200
1024	0.91	1.81	3.63	7.25	14.50	29	58	116
512 Zoom	0.23	0.46	0.93	1.85	3.70	7.4	14.8	29.6
1024 Zoom	0.11	0.23	0.45	0.90	1.80	3.6	7.2	14.4

Aside from FFT analysis features, The Kay DSP provides a variety of other capabilities which made the equipment ideal for acoustic analysis, among them:

- Dual channel recording of input signals permits comparison of two signals
- immediate storage of incoming signals in a memory buffer
- available split screen display, permits simultaneous analyses of multiple signals
- frequency expansion of portions of the recorded signal allows detailed identification of key features

The above information is not intended to be an exhaustive listing of the DSP capabilities, but rather an overview of key features used or at least explored during the research process. For an in-depth analysis of the DSP features, refer to the KAY Model 5500-1 Sonograph User's Manual.

Analysis Capabilities

Five analysis modes were accessible using the DSP. Of these, only three were used extensively during the research. These were the waveform, power spectrum, and spectrographic displays. An explanation of each is provided below.

Waveform Display

The waveform display, as illustrated previously in Figure 2.4, represents the input signal in terms of time (x-axis) vs. amplitude (y-axis). The amplitude level displayed in this analysis mode represents the composite energy level of all component frequencies which make up the sound.

Analysis of signals using this format serves two key functions. First, it provides a very basic yet reliable means of identifying and eliminating signals which are not representative of mechanized equipment (ie. steady state waveforms). Second, through visual analysis of the amplitude levels over time, it is possible to isolate a time interval of 6-8 seconds over which the signal is strongest. This corresponds to a time interval when the signal source is closest to the recording station.

Power Spectrum

The power spectrum display, as illustrated in Figure 2.5, provides a graphical representation of the energy distribution of the sound in terms of frequency level over a "slice of time". The slice of time over which spectral analyses are performed may be adjusted to range from 20 milliseconds to several minutes. The energy levels reflected through this analysis represent time-averaged levels for the window of time selected.

Through visual observation of spectral profiles, distinctive traits can be identified which collectively can be used to distinguish one source of sound from another. Key features discemable from power spectrum displays which are useful for "acoustic fingerprinting" include:

- upper frequency limit of acoustic profile
- frequency level at which acoustic energy is strongest
- presence of any gaps in the acoustic profile where energy level is zero decibels
- distinctive power spikes within the acoustic profile

An example of how these traits may be used to distinguish among types of construction equipment is illustrated in Figure 2.6, demonstrating acoustic differences between an off-road dump truck and a water truck.

Spectrograph

Spectrographs, as illustrated in Figure 2.7, are three dimensional displays showing a time history of the sound in terms of component frequencies and their respective intensity levels. Under this analysis format, time is represented along the x-axis, frequency is represented along the y-axis, and power level is represented in terms of grey level along the z-axis.

In essence, spectrographic displays are a compilation of back-to-back slices of power spectrum displays rotated about the z-axis, This is demonstrated in figure 2.8. The unique feature which makes spectrographs a powerful analysis tool is that they provide a visual representation of spectral changes over time.

As will be demonstrated later, the specific orientation of both harmonic and transient patterns within the spectrographic displays provides important information about the equipment source.

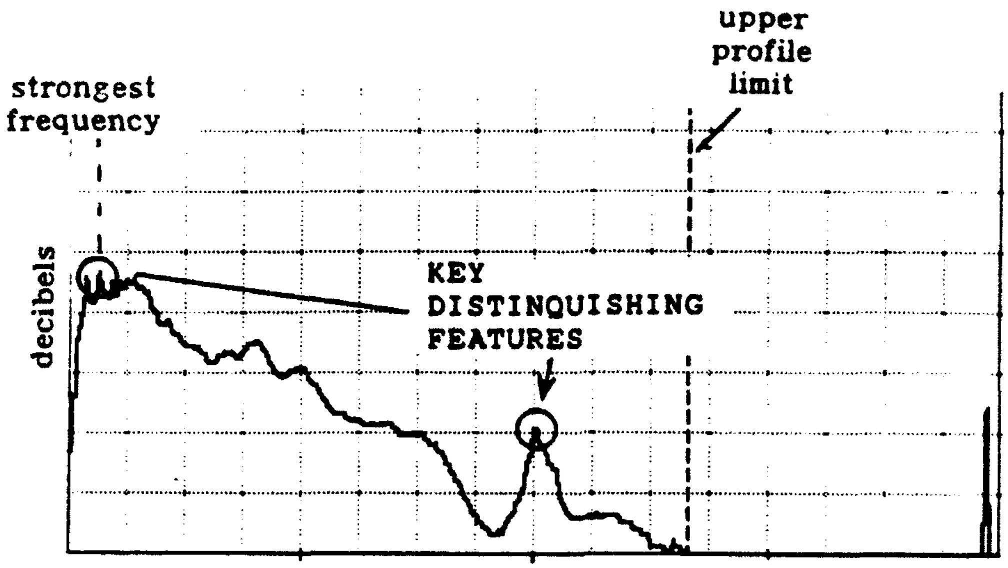


Figure 2.5: Sample Power Spectrum Display

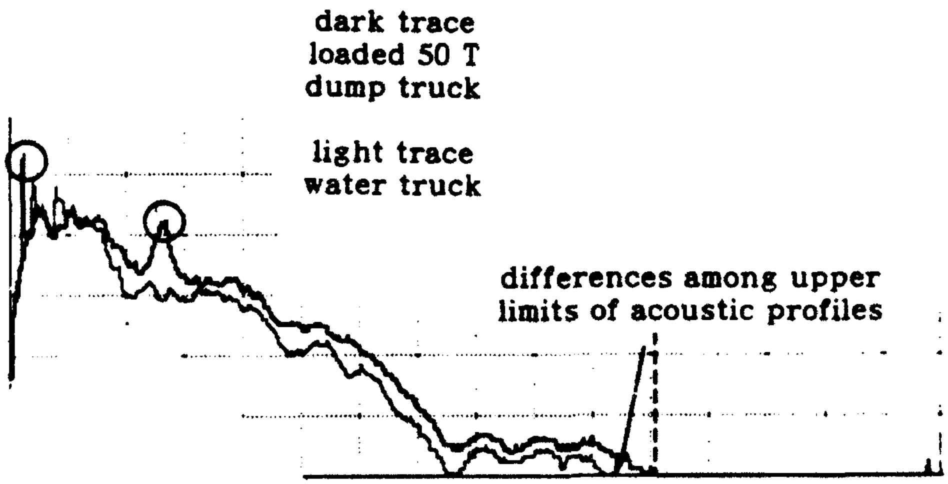


Figure 2.6: Comparison of Spectral Traits as Means of Distinguishing Among Types of Equipment

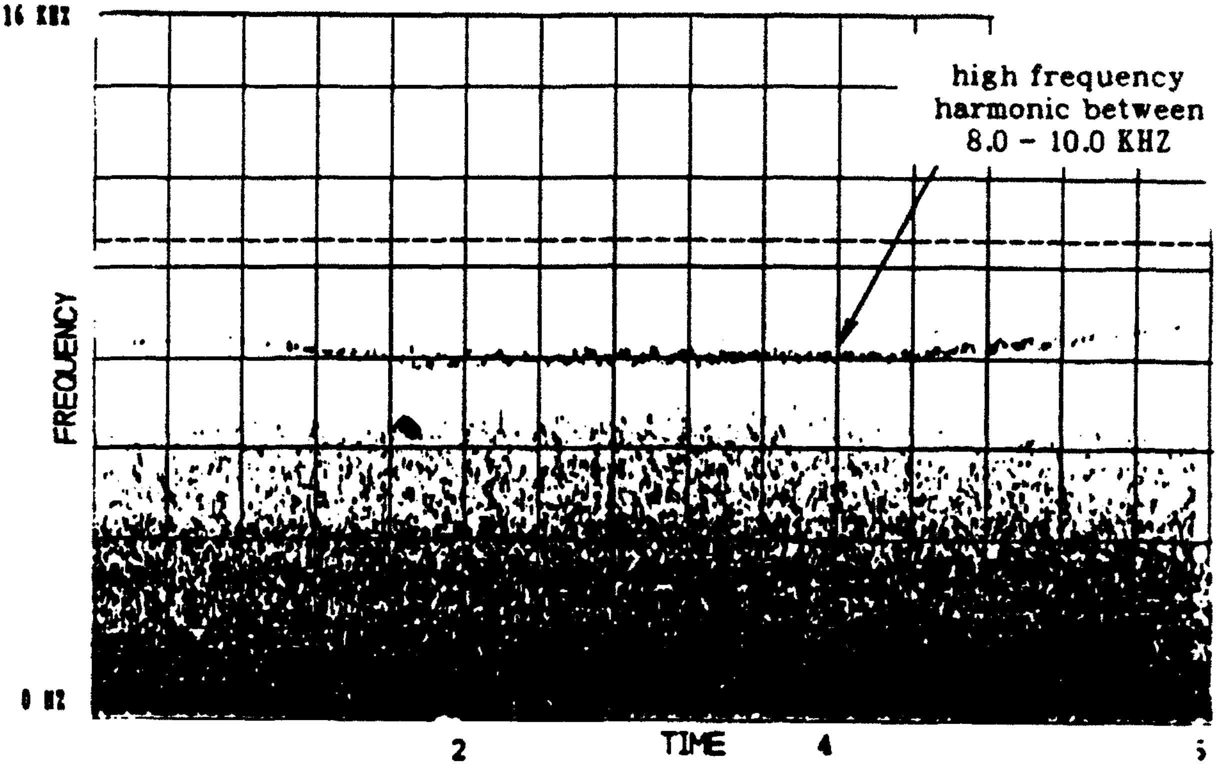


Figure 2.7: Sample Spectrographic Display

Summary

Information presented in this chapter provides an overview of key acoustic principles and analysis modes used during the course of this study for characterization of construction equipment sounds. The following chapters will now proceed to address how the acoustic data were collected and analyzed.

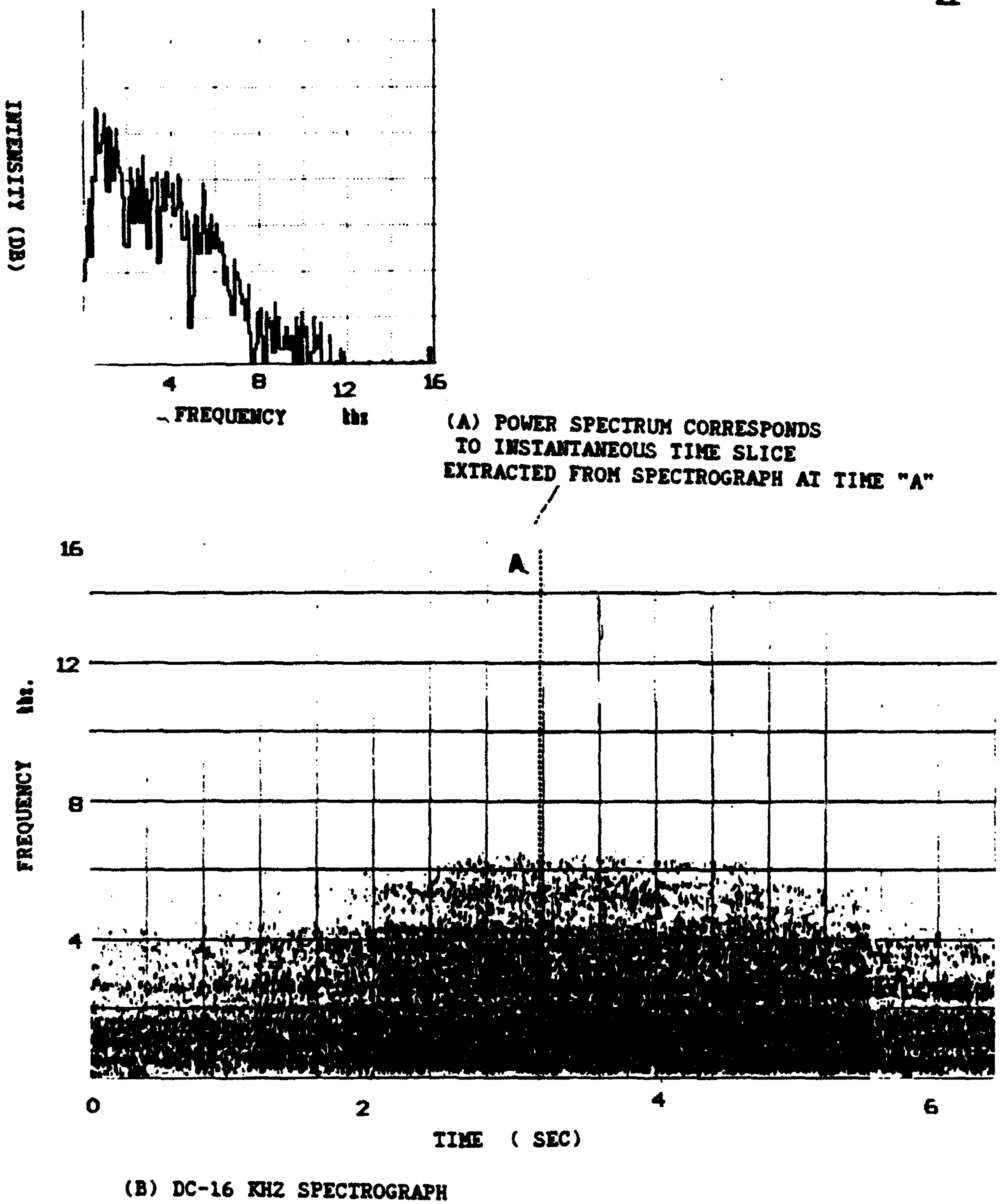


Figure 2.8: Correlation Between Power Spectrum Display and Spectrographic Display

CHAPTER 3

DATA COLLECTION

Overview

Collection of data under actual field conditions was a primary feature of this research. As with any field analysis, however, there were a number of variables (atmospheric and site conditions) known to have an impact on the consistency of results. To minimize the chances of variability under this initial study, efforts were made to establish consistent criteria under which data were collected.

This chapter summarizes the information that was collected, where it was collected, the equipment used, and the criteria under which data were recorded.

Data Sources

Acoustics for the six types of construction equipment listed in Table 3.1 were collected for analysis. Hauling units were recorded under both loaded and empty conditions.

Table 3.1 Summary of Acoustic Samples Collected

Equipment/ Load Status		Units Sampled	No. Acoustic Samples
1(a).	CAT scraper (loaded)	3	12
1(b).	CAT scraper (empty)	3	12
2(a).	Euclid 50 T dump truck (loaded)	5	15
2(b).	Euclid 50 T dump truck (empty)	5	15
3(a).	Euclid 75 T dump truck (loaded)	3	3
3(b).	Euclid 75 T dump truck (empty)	3	3
4.	CAT D8N bulldozer	2	4
5.	Mack 6200 gallon water truck	1	2
6.	Ford F-150 pick-up truck	1	2
	TOTALS:	26	68

The data were recorded at three project sites. These sites included the Reading Anthracite Coal Mine in Duncott, Pennsylvania; a shopping center under construction in Lewistown, Pennsylvania; and the Glen O. Hawbaker mineral products quarry in Pleasant Gap, Pennsylvania.

At each job site, a common path was used for haul and return routes. In all instances, hauling operations were organized in such a manner that permitted loaded equipment to travel either horizontally or slightly down grade, thus taking maximum advantage of gravity to assist with transportation of the load. Figure 3.1 illustrates how these haul routes were set up and where recording equipment was stationed.

Data Collection Equipment

Hauling operations were recorded using a Panasonic camcorder model VW3250/8AF positioned at a stationary location on site. The camcorder's built-in microphone, was used as the audio sensor.

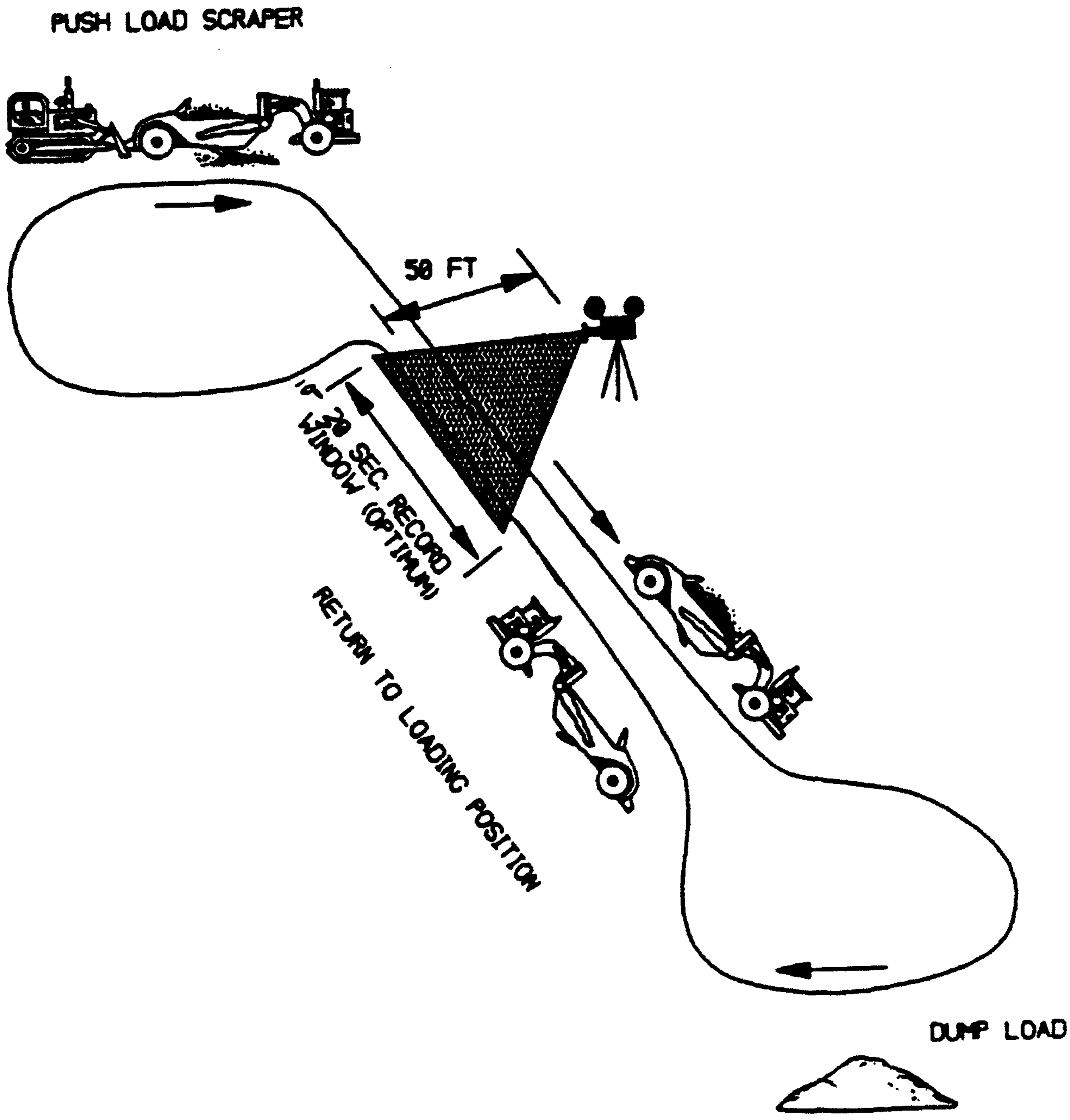


Figure 3.1: Set-up of Data Collection Equipment in Relation to Haul Routes

Video cassettes were specifically used in lieu of audio cassettes because of the added advantage of being able to visually correlate production sounds to a specific piece of equipment.

Control Variables

Prior to data collection, it was known that a variety of physical and environmental factors could affect the consistency of acoustic data. Known variables included:

- wind/temperature/humidity
- effect of terrain on sound propagation of certain frequencies ranges (amplification or attenuation)
- haul route grade
- vehicle speed
- differences in mechanical condition between of same type of equipment
- distance between sound source and recording unit

While it was deemed impossible to control the effect of all variables, several guidelines were implemented to maximize consistency of the data collected. Guidelines used are as follows:

A. Standardized distance from source to recorder.

At all sites, the camcorder was set up approximately 50 feet from the centerline of the haul road.

B. Temperature and Humidity.

In all cases data was collected during afternoon hours, in clear weather, with temperatures ranging from 50 - 80 F.

C. Terrain/Grade.

Hauling operations were recorded only along sections of relatively level sections of terrain, with grades less than 3 percent.

Using the above criteria, data were collected on five occasions for periods ranging from 30 minutes to 2 hours. A total of 68 acoustic samples were obtained. These samples were reflective of 15 individual units of equipment, comprising 6 separate and distinct types.

Summary

Information presented in this chapter summarized what data was collected, where it was collected, the manner in which it was collected, and the equipment used. The next chapter addresses how the data was analyzed and characteristics used to distinguish one source from another.

CHAPTER 4
SIGNAL ANALYSIS

Overview

This chapter explains the procedures used to identify key acoustic features of the various construction equipment listed in Table 3.1. Due to the limited number of acoustic samples analyzed, this report does not chart all acoustic profile features of each piece of equipment studied. Rather the features of each profile are identified in a "qualitative" manner.

The chapter is divided into three parts: The first addresses the procedures used to input the samples into the DSP. The second addresses the analysis formats used and the results observed. The third provides an observation summary.

Data Processing - Signal Input

Using video tapes containing the field data, footage was converted into useful acoustic information by playing the tape through a VCR/monitor interfaced with the DSP. As the tape was played, segments were screened to identify periods of activity in which single construction units were observed. Periods of multiple vehicle activity were disregarded from this study for the sake of simplicity. The audio portions of the individual construction units were then transferred to the DSP's memory buffer. Once stored in the buffer, multiple analyses were performed.

Types of Analysis Performed

Two forms of signal analyses were performed on each acoustic sample: spectral analysis (Power Spectrum display) and spectrographic analysis. As described in Chapter 2, each format offers several strengths and weaknesses; however, when used together, a detailed analysis of an acoustic signature is possible.

Using the processing capabilities of KAY 5500 DSP, it is possible to perform both analysis formats simultaneously using a split screen display. This proved to be very beneficial in correlating traits from one display to another.

Spectral Analysis

Early in the analysis phase, it was determined that the acoustic signatures of all mechanized equipment under this study fell within the range of 0-16 khz. Accordingly, the frequency range settings used for spectral analysis were set using the limits described above. Maximum frequency resolution was also used by setting the FFT transform to the highest available setting (1024 points) for processing of the signal. The resultant settings enabled each sample's entire acoustic profile to be displayed on the screen, with data points recorded every 20 hz.

Experimentation was performed using alternate frequency ranges and transform sizes; however, the degree of information attainable did not substantially improve. Consequently, no other analysis windows other than 0 - 16 Khz with a transform size of 1024 points were used for all spectral analyses.

Table 4.1: Summary of Key Spectral Features Observed From Equipment Samples

EQUIPMENT TYPE	UPPER PROFILE LIMIT	STRONGEST FREQUENCY	PROFILE GAPS	OTHER DISTINCT TRAITS
1. Loaded Cat Scraper	10.8 - 11.0 khz	320 - 920 hz	None	Consistent ower spike present among all samples within the range of 3.2 - 3.5 khz
2. Empty Cat Scraper	11.5 - 12.0 khz	320 -920 hz	Residual Energy levels above 11.2 khz	Sharp power spikes consistently present within the the following ranges: 280 -320 hz 800 -1000 hz 1250 - 1600 hz
3. Loaded 50 T dump Truck	12.5 - 12.7 khz	2.3 - 2.8 khz	None	Massive power spike present in range of 2.3 - 2.8 khz dominates all profile features. No other equipment exhibits such a distinct concentration of energy in this frequency range.
4. Empty 50 T Dump Truck	12.1 - 13.1 khz	320 - 1600 hz	None	Fairly consistent energy levels exist among frequencies between 320-1600 hz generating a wide energy plateau at low end of profile. Also identifiable is power spike in range of 2.3-2.8 khz but energy level is significantly lower than exhibited by loaded dump truck.
5. Loaded 75 T dump Truck	10.7 - 11.0 khz	320 - 1080 hz	None	Three sharp energy spikes consistently present among samples in low frequency ranges. Approximate locations as follows: 280 - 320 hz 500 - 600 hz 900- 1100 hz weaker, more subtle energy concentrations present in range of 6000 hz, 8000 hz, and 9500 hz

Table 4.1 : [continued]

EQUIPMENT TYPE	UPPER PROFILE LIMIT	STRONGEST FREQUENCY	PROFILE GAPS	OTHER DISTINCT TRAITS
6. Empty 75 T Dump Truck	10.6 - 11.7 khz	320 - 1080 hz	None	Massive high frequency power spike present among all samples within the range of 8.0 -10.0 khz. Additionally, two distinct power spikes present over the low frequency ranges. Locations as follows: 280- 320 hz & 520- 720 hz.
7. Water Truck	10.0 - 10.2 khz	240 - 280 hz	7.4 - 7.6 khz	Very sharp, distinct power spike visible in range of 240 -280 hz. Maximum energy level of profile consistently present within this narrow frequency range. Also, upper limit of acoustic profile of the water truck is significantly lower than the acoustic limits of scrapers and dumps studied.
8. Bulldozer	12.0 - 12.4 khz	800 - 1050 hz	11.0 - 11.8 khz	A 500 hz band of substantially elevated energy in relation to adjacent frequencies is observable between 600 - 1100 hz. Also, Five power spikes are consistently present among samples, above 2000 hz. Approximate ranges as follows: 2000 - 2200 hz 6200 - 6500 hz 2600 - 2800 hz 8200 - 8400 hz 3200 - 3400 hz
9. Ford F-150 Pick-up	11.0 - 11.3 khz	400 - 500 hz	Residual levels above 10.5 khz	Decibel level of component sounds over low frequency ranges (below 1000 hz) are considerably lower than the recorded levels from other equipment samples. Aside from that, no unique spectral features are readily observable.

Analyses were initiated by generating an average acoustic profile of the signal over a six second window in which the signal was strongest. Once generated, the profile was visually inspected for consistent features capable of distinguishing one type of equipment from another.

Identifiable Features

Spectral analyses were used primarily for identification of acoustic features on a macro level. Identifiable characteristics capable of being determined using this analysis mode included:

- Upper frequency limit of acoustic profile
- frequency level at which maximum acoustic energy was transmitted
- gaps in acoustic profile (i.e. frequency ranges with 0 db sound energy)
- Prominent features (power spikes or troughs) in profile

Results of Spectral Analysis

A total of 68 acoustic samples were analyzed via spectral analyses. Results confirmed the assumption that each type of equipment and load status generates a unique acoustic signature, distinctive from all others. Table 4.1 provides a summary of key spectral features which were found to distinctively characterize each type of equipment studied. Representative spectrographic output of equipment sampled can be found in Appendix A.

The displays referenced above are representative samples and some variability was observed with respect to exact position of the features among various samples. The degree of variability was not however considered to be significant. For example, the upper limit of the acoustic profile observed for 12 loaded scraper samples was found to range between 10.8-11.1 khz. Based upon comparative analysis of spectral features among identical equipment samples, it was determined that substantial consistency does exist to warrant use of these features as representative acoustic traits.

One general observation must be made at this point with respect to inaccuracies in the spectral analysis results. That is, a sharp energy spike is consistently present in the range of 14 khz among all samples. Based on the consistency of this feature, it is believed that the spike is reflective of electrical noise emanating from the camcorder. To eliminate this inaccuracy in future research efforts, it is recommended that a high resolution microphone be established at a remote location (at least 25 feet from the video camera) for future data collection efforts.

Spectrographic Analysis

Spectrographic analyses were performed for the purpose of identifying specific harmonic features.

As an explanation of the significance of these features, recall that previously in Chapter 2 it was explained that virtually all sounds comprise a number of simple tones. Sounds emitted by construction equipment fall into this category. While the principal

contributor of the vehicle sound is muffler exhaust, a variety of other system components contribute to the acoustic signature. Many of these components exhibit specific tone frequencies which can be readily detected through spectrographic analyses. Mechanical components include engine intake and exhaust, cooling system fans, turbochargers, transmission gear noises, even tread slap. With tracked equipment, the sound of steel sprockets acting on the track pins is also readily identifiable.

Consequently, by knowing key mechanical data about a given type of construction equipment, an acoustic template can conceivably be generated which reflects the specific spectral features each component contributes to the overall spectrographic profile. Knowing for instance that the turbo charger on a 75 Ton Euclid truck runs independently of the engine and operates at a range of 3000-7000 hz can greatly assist one in identifying or disqualifying a signal as representative of a Euclid truck.

Efforts to identify and map specific features representing system components of each type of equipment were considered to be beyond the scope of this study. Spectrographic analyses were performed here to identify the presence of different harmonic features among samples; no attempt was made to identify the mechanical source corresponding to each acoustic feature.

The range over which key spectrographic features could be found was a key concern of the analysis phase. Conversations with acoustical experts indicated that the most revealing spectrographic information would likely be found in the lower

frequency ranges, generally 0 - 1000 hz. However, three levels of spectrographic analysis were performed for thoroughness:

0 - 2 KHZ

0 - 8 KHZ

0 - 16 KHZ

Results of Analysis, 0 - 2 KHZ

Analyses of signals over the range of 0 - 2 KHZ did reveal distinct harmonic features sufficient to distinguish one type of equipment from another. These features can be visually observed through comparison of Figures B.1 - 9 in Appendix B. Several problems were however observed at this level of analysis. First, due to the type of recording equipment used, low frequency sounds (100 hz and below) were not recorded. Generally, key distinguishing harmonic patterns should be easily identifiable in this range. Results indicated that wind filters in the camcorder microphone blocked out most acoustic data in this range. Secondly, comparison of samples among the same type of equipment revealed some variability with regard to harmonic patterns. Variability among samples ranged from number of harmonic lines within a given frequency range to the location of harmonic lines with respect to frequency. Despite the variability and loss of low frequency data, numerous spectrographic features were consistently present to uniquely distinguish one source of equipment from another.

Results of Analysis 0 - 8 KHZ

Analyses of signals over the expanded range of 0 - 8 khz revealed further key features capable of facilitating identification of equipment sources. A complete representation of spectrographic profiles over the range of 0 - 8 khz for each type of equipment are provided in Appendix C. Key features were particularly visible in this range for loaded the 50 T dump trucks, 75 T dump trucks, and bulldozer. The spectrographic profile representative of a loaded 50 T dump, for instance, exhibits a very thick band of energy (approximately 100 hz wide) located in the range of 2500 hz. Alternately the spectrographic profile representative of empty 75 T dump trucks possesses a readily distinguishable harmonic which fluctuates over the range of 3 - 7 khz. The spectrograph representative of the bulldozer, on the other hand, possesses vertical spectral lines spaced approximately 0.15 seconds apart.

Results of Analysis 0 - 16 KHZ

Spectrographic analysis of signals above the frequency range of 8 khz failed to reveal any further distinguishing features among equipment samples with exception of empty 75 T Euclid trucks. Analysis indicated that 75 T trucks exhibited a harmonic line between the range of 8 - 10 khz while traversing a level or slight grade while empty. All other equipment samples failed to reveal any distinctive traits. Copies of the 0 - 16 KHZ spectrographs representative of the equipment sampled are provided in Appendix D.

The consistent lack of identifiable features at higher frequency ranges support the fact that high frequency tones do not propagate as far as low frequency tones.

Table 4.2 Summary of Key Spectrographic Features

EQUIPMENT TYPE	DC - 2 khz Features	2 - 8 khz Features	8 - 16 khz Features
Loaded Cat Scraper	• 4-6 harmonics were present between 100-400 hz. Harmonics at 220 & 320 hz were most distinguishable along trailing edge of spectrograph. • A Strong harmonic band was present in 80% of samples over range of 900-1020 hz. Feature was most visible over 4-6 sec. as scraper passes recording station. • Brief transient signals of approx. 1 sec. in duration observable over 8-10 sec time frame as scraper approaches recording station. Signal are quasi-sinusoidal in shape & exhibit and amplitude span of approx. 50 hz.	• 3 concentric harmonic lines present in the range of 3000-4000 hz. Harmonics most visible over 3-4 sec. window while scraper is in front of the recording station.	• No specific features noted other than a general observation that as shown by the DC-16 khz spectrograph, the majority of acoustic energy for the scrapers concentrated below 4000 hz.
Empty Cat Scraper	• 5 harmonic bands observed within the range of 100-400 hz. Four bands are concentric in orientation & exhibit doppler effect as vehicle passes. One harmonic at approx. 200 hz exhibits a level trace over the time history. •Within the range of 1350-1550 two harmonic bands exist,spaced approx. 100 hz apart. The bands exhibit a slight negative slope from left to right and are generally visible over a 4- 6 second window as the vehicle passes the recording station.	• Harmonic band consistently appears in the range of 3000-3500 hz. 2nd band of lesser intensity is generally visible in the vicinity of 2500 hz. • A brief versicle band of concentrated energy spanning the range 0-6000 hz is generated as the scraper passes the recording station. This spectral trait spans approximately 0.5 sec. in duration and is unique to loaded scrapers. This trait may be used as a primary identification feature.	• No additional features visible over higher frequency ranges
Loaded 50 T Dump	• Few acoustic features are discernable below 2000 hz.. Relative energy levels of adjacent features are very similar producing minimal gray level contrasts to identify features. Of 15 samples analyzed, only 2 consistent features were observed. These include: (a) a level harmonic band at 420 hz present over the entire time history display, (b) a harmonic band present over the range of 1500-1700 hz.	• A thick band of concentrated energy is consistently visible in the range of 2400- 2800 hz. The band is visible over the entire time history display and is approximately 100 hz wide. It exhibits extremely high intensity levels. This feature is unique to loaded 50 ton dump trucks and may be used as a primary means of identification. • A second, less conspicuous feature is also visible in the form of a harmonic line, present over the range of 3200 - 4000 hz.	No specific spectrographic traits are visible over the higher energy levels. Broad overall analysis of the DC -16 KHZ spectrograph does provide some information on the general shape of the sample's spectrographic profile. observations indicate that the majority of acoustic energy is concentrated below 4000 hz except for a 4- 6 second window when the truck passes in front of the recording station. during this time-frame, frequency components between 4.0 -6.0 khz exhibit elevated energy levels, producing a "dome- like effect along the upper edge of the profile.

Table 4.2 : [continued]

EQUIPMENT TYPE	DC – 2 khz Features	2 – 8 khz Features	8 – 16 khz Features
Empty 50 T Dump	• Within this range, weak concentric harmonic lines are visible over a majority of the profile, spaced approximately 25 hz apart. These harmonics begin a approximately 150 hz and extend through 1800 hz.	• The DC – 8 khz spectrograph exhibits 6 – 8 harmonic lines spaced approximately 500 hz apart, beginning at approximately 200 hz and running through 4000 hz.	No additional features were detected within this range.
Loaded 75 T Dump	• Four harmonic lines are consistently visible within the range of 150 – 350 hz. • Additional harmonic lines are consistently present within the following ranges: 490 – 600 hz 700 – 755 hz 950 – 1250 hz	• Loaded 75 Ton dump trucks consistently displayed a single harmonic within the range of 3.0 – 7.0 khz, fluctuating in terms of frequency over the time history display. This harmonic feature was unique to loaded 75 ton dump trucks and provided a strong identification feature for samples.	No additional spectrographic features were detected within this range.
Empty 75 T Dump	• The spectrographic profile below 2 khz was characterized by 6 – 8 strong harmonic bands focussed between DC – 1400 khz. Interspersed with the strong harmonic bands were 4 weak harmonic bands, typically visible in the range of 100 – 400 hz. The strong harmonic bands were found to exist within the following frequency ranges: 220 – 250 hz 745 – 845 hz 280 – 320 hz 880 – 1110 hz 495 – 560 hz 1200 – 1400 hz	• Between 2 – 8 khz, empty 75 ton dump truck samples exhibited 1- 2 harmonic features. (Several samples exhibited only one sample, but one exhibited two). The first harmonic, observed in all samples, was found to exist in the range of 5.0 – 7.0 khz, and fluctuate in terms of frequency level over time. (This could be indicative of the truck's turbo charger since the trucks were operating up a slight grade while empty.) the second harmonic observed in one sample was found to exist in the range of 6.0 – 8.0 khz and follow the same general pattern as the lower harmonic. This harmonic could perhaps be indicative of an engaged air conditioning system on the truck.	Above 8 khz, all empty 75 ton dump trucks samples exhibited a strong harmonic in the range of 8 – 10 khz. The source of this feature is unknown. This trait, however is unique to empty 75 ton dump trucks and provides a strong source of vehicle identification.

Table 4.2 : [continued]

EQUIPMENT TYPE	DC - 2 khz Features	2 - 8 khz Features	8 - 16 khz Features
Water Truck	In excess of 30 harmonic bands dominate the DC - 2 khz spectrograph of the water truck. Analysis of the bands indicate that a total of 4 fundamental tones exist within the range of 200 - 400 hz, followed by multiple overtones of each. Two of the harmonic patterns possess strong levels of intensity, two are weak. Fundamental tones are as follows: Fundamental 1 - 220 hz (strong) Fundamental 2 - 320 hz (weak) Fundamental 3 - 350 hz (weak) Fundamental 4 - 400 hz (strong) * This strong harmonic pattern is a key distinguishing feature .	• No additional spectrographic features useful for identification of the water truck were detected within the range of 2 - 8 khz.	No spectrographic features capable of assisting with identification of the water truck were detected above 8 khz.
D8N Bulldozer	Within the bottom 500 hz of the spectrographic profile , five harmonic bands were consistently observed. Analysis indicated that the harmonic features consisted of two fundamental tones and three overtones: Fundamental "A" 110 hz overtone 1 220 hz overtone 2 435 hz Fundamental "B" 155 hz overtone 1 315 hz Also readily noticeable was a wide band of concentrated acoustic energy between 625 - 1200 hz.	• Vertical spectral lines spaced approximately 0.15 seconds apart over the entire time history of the spectrograph uniquely distinguish the bulldozer's acoustic profile from all other construction equipment sampled. (The vertical lines are indicative of tracked equipment.) • Other spectrographic features observed were 4 harmonic lines between 2000 - 3500 hz. Approximate location of the observed harmonics are as follows: 2100 hz 2800 hz 2600 hz 3200 hz	No additional spectrographic features were detected within this range.

Table 4.2: [continued]

EQUIPMENT TYPE	DC - 2 khz Features	2 - 8 khz Features	8 - 16 khz Features
Ford F-150 Pickup	• Four weak but continuous harmonic lines were consistently observed between 150-450 hz along the leading edge of the profiles. These provided advance notice of the approaching vehicle. Approximate frequencies where these harmonics were observed are as follows: 150hz, 220 hz, 325 hz, 425 hz. • Three brief but intense harmonic bands were observed in the range of 440 - 480 hz corresponding to engine noise as the vehicle accelerated. An additional harmonic was also consistently observed in there range of approximately 880 hz and likewise appeared related to engine noise, displaying a increasing frequency as the vehicle accelerated	• The majority of acoustic energy of the profile was concentrated below 2000 hz. Only two features harmonic features were observed above that range - one harmonic present at approximately 2500 hz and a second at approximately 3800 hz.	No additional spectrographic features were detected within this range.

Summary of Observed Spectrographic Features

Table 4.2 provides a summary of key spectrographic features which were found to distinctively characterize each type of equipment studied.

Summary of Observations

Results of spectral and spectrographic analysis indicate that acoustic sensory technology is a feasible means of equipment identification. Results further confirm that sufficient spectral differences do exist among loaded and empty equipment samples to permit determination of load status (i.e., loaded or unloaded). Mapping of specific acoustic features capable of definitively distinguishing one type of equipment from others was beyond the scope of this civil engineering study.

Assuming that acoustic features can be reliably mapped, the next step in implementing such technology would be to develop a signal processing program capable of identifying the equipment source based on its signature. Such signal processing capabilities currently exist, and could be easily adapted to this application.

Assuming all above interdisciplinary developmental stages can be completed, acoustic sensory technology can be applied to a variety of construction applications. The next chapter will address several of these applications from a conceptual viewpoint.

CHAPTER 5

APPLICATIONS

Overview

Information presented in the previous chapters outlined how acoustic sensing may be used to identify construction equipment. The focus now shifts to a discussion of how such technology can be used for construction applications. Three application areas will be discussed: Productivity measurement, safety/traffic control, and security. An economic analysis will be provided at the end of this Chapter

Productivity Data Collection

As indicated in Chapter 4, hauling units exhibit noticeable differences in their acoustic profiles when loaded as opposed to empty. This observation was consistent among all three types of hauling units studied. Thus, it appears reasonable that if separate acoustical templates are established for each type of hauling unit under loaded and empty conditions, a signal processing program could be developed that is capable of automatically determining load counts using a daily acoustic record of hauling activity.

Such a system could generate the following productivity information:

- total daily load count
- load count break down per hour
- periods of inactivity

The advantages of an automated data collection system for hauling operations are numerous. First, although some initial capital investment is needed, the operational costs of an automated system are minimal compared to wages of personnel paid to manually collect the same information. Second, automated systems are less prone to errors than are manual systems. Third, processing time of data is minimal; results of analysis could be generated in a matter of minutes as opposed to days using manual methods. Also, the information attainable could be easily reconfigured into a variety of sorted reports for use by different levels of management with minimal effort. Lastly, automated systems could be adapted to function in adverse weather (extreme cold, rain) when human observation would not otherwise be recommended [O'Brian 1985].

Traffic Control/Safety

On any construction site where numerous pieces of construction equipment operate simultaneously, some form of traffic control is needed. Nowhere however is the need for traffic control more heightened than on hauling operations, where trucks and/or scrapers operating at speeds of up to 35 mph transport heavy payloads along relatively narrow sections of road frequently used for two way traffic. In addition to congestion, a variety of potentially hazardous traffic conditions may exist along these routes, which if left uncontrolled could affect the efficiency and safety of operations. Typical hazards in which some type of traffic control would be needed include:

- Intersections where haul routes cross public roads
- blind turns where opposing traffic (two way traffic) could be encountered
- choke points along haul route (i.e., one lane bridges)

Through use of a system of acoustic sensors and a simple signal processing program, a warning system of flashing signs could be implemented warning of approaching traffic. This concept is illustrated in Figure 5.1. By implementing of a series of sensors, a vector of the sound source can be detected several hundred feet in advance of each end of the hazard area. An electronic signal could be sent, initiating a flashing warning sign at the other end to warn oncoming vehicles of traffic in the hazard area. Upon detection of a subsequent sound vector indicating that the vehicle has passed the hazard area, the flashing warning signal would be terminated.

While alternative traffic warning systems are currently in use, ranging in complexity from simple stationary signs to pressure activated sensory systems which activate flashers, a system utilizing acoustic sensory technology offers several advantages. First, such a system could be portable, activated through electronic signals vice hard wiring. Second, such systems are unaffected by severe weather (snow, mud) which might clog or render other systems inoperable.

Security

Theft and vandalism is a major concern to any contractor. The tools, materials, and equipment stored on site represent a significant investment to the contractor. One piece of heavy construction equipment, for instance, represents a capital investment of \$100 K - \$500 K. Loss or damage to any of these items can quickly erode the profit margin that contractors may have anticipated to make on a project.

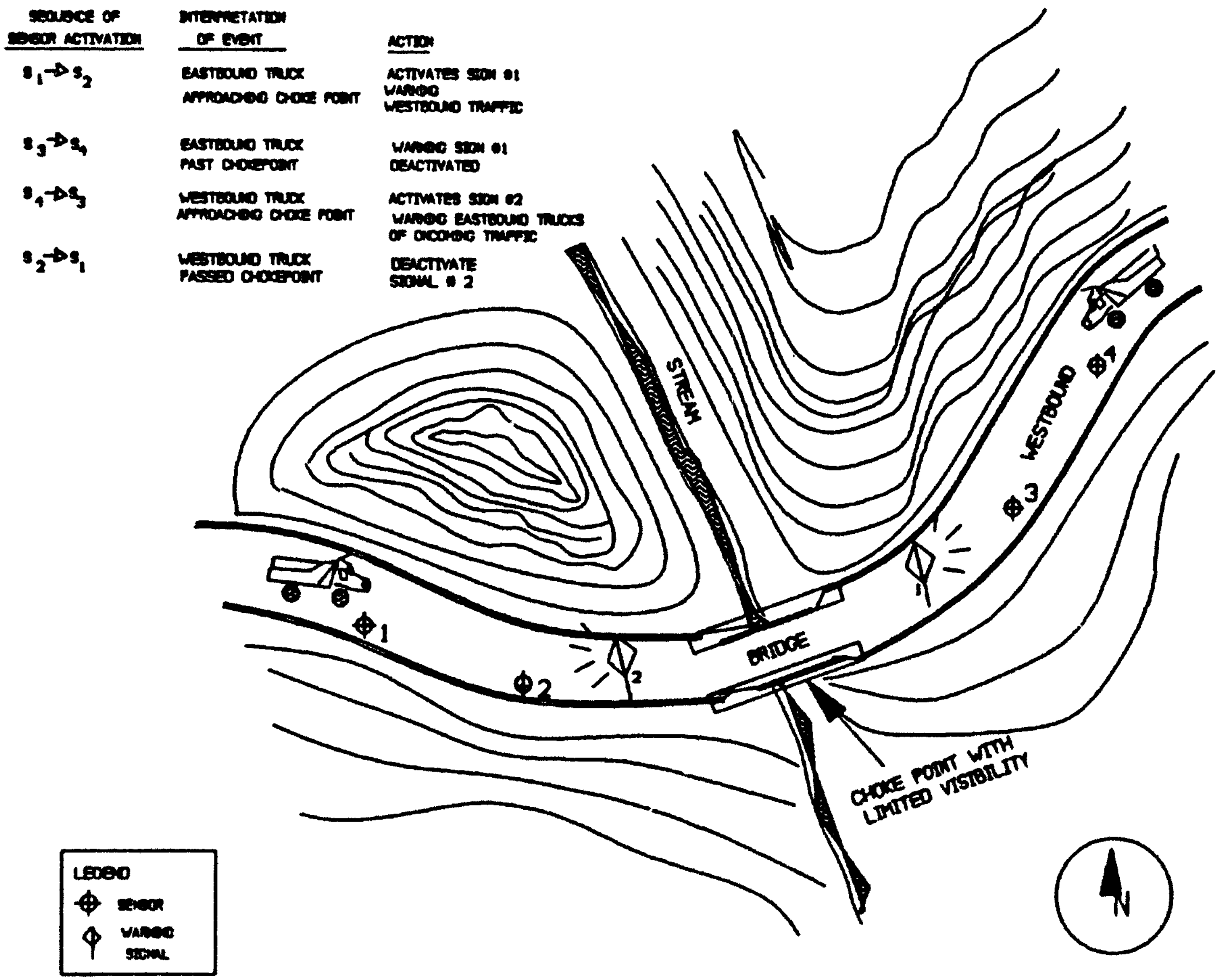


Figure 5.1: Application of Sensory Technology for Traffic Control

To protect their interests, contractors have implemented a range of security measures aimed at deterring vandalism or theft. Among security measures now commonly used include:

- high security fencing around the perimeter of jobsites
- installation of hidden "kill switches" on ignition systems of heavy equipment
- use of key control systems to provide limited access to highly pilferable areas

While the above measures are somewhat effective with regard to loss prevention, they provide no means of detecting acts of theft or trespass in progress. This inherent weakness is particularly a problem on project sites located in remote or sparsely populated areas, where no observation by traffic and neighboring properties allows additional time in overcoming in-place security measures without the threat of detection.

Adaptation of acoustic sensing technology for surveillance of job sites offers a useful solution to current security weaknesses. From a conceptual viewpoint, a viable surveillance system could be developed by monitoring after hours acoustic activity at a construction site, and comparing signals received against specific acoustic patterns designated as potential "threats". Specific threats which could be detected through a signal recognition algorithm include:

- foot traffic inside the project site
- opening of doors or windows
- human voice patterns
- start-up of automotive or construction equipment within the project perimeter

Surveillance would be achieved through use of acoustic sensors positioned at strategic locations throughout the site, and wired directly to a processing unit capable of analyzing and comparing the signals against specific threats under real time conditions, Figure 5.2.

Activation of an alarm system would occur in instances where the signal received matched the pattern of one of programmed threats in the system's data bank. Alarms could range from a high intensity acoustic sound to activation of spot lights to initiation of a signal to the local police department. Through simplistic processing, a time delay could also be implemented into the system to allow the contractor's forces to deactivate the system prior to initiation of an unwarranted alarm signal. From an economic analysis perspective, automated data acquisition systems are a worthwhile investment. The cost of procurement for the Kay model 5000 Digital signal processing equipment in 1990, for instance, was approximately $25,000. Assuming that durable, high fidelity recording equipment could be obtained for approximately $1000, and pattern recognition software programs could be developed for approximately $3000 to $5000, an entire productivity monitoring set-up would cost approximately $30,000. Such an estimate is conservative, however, since procurement costs would likely drop

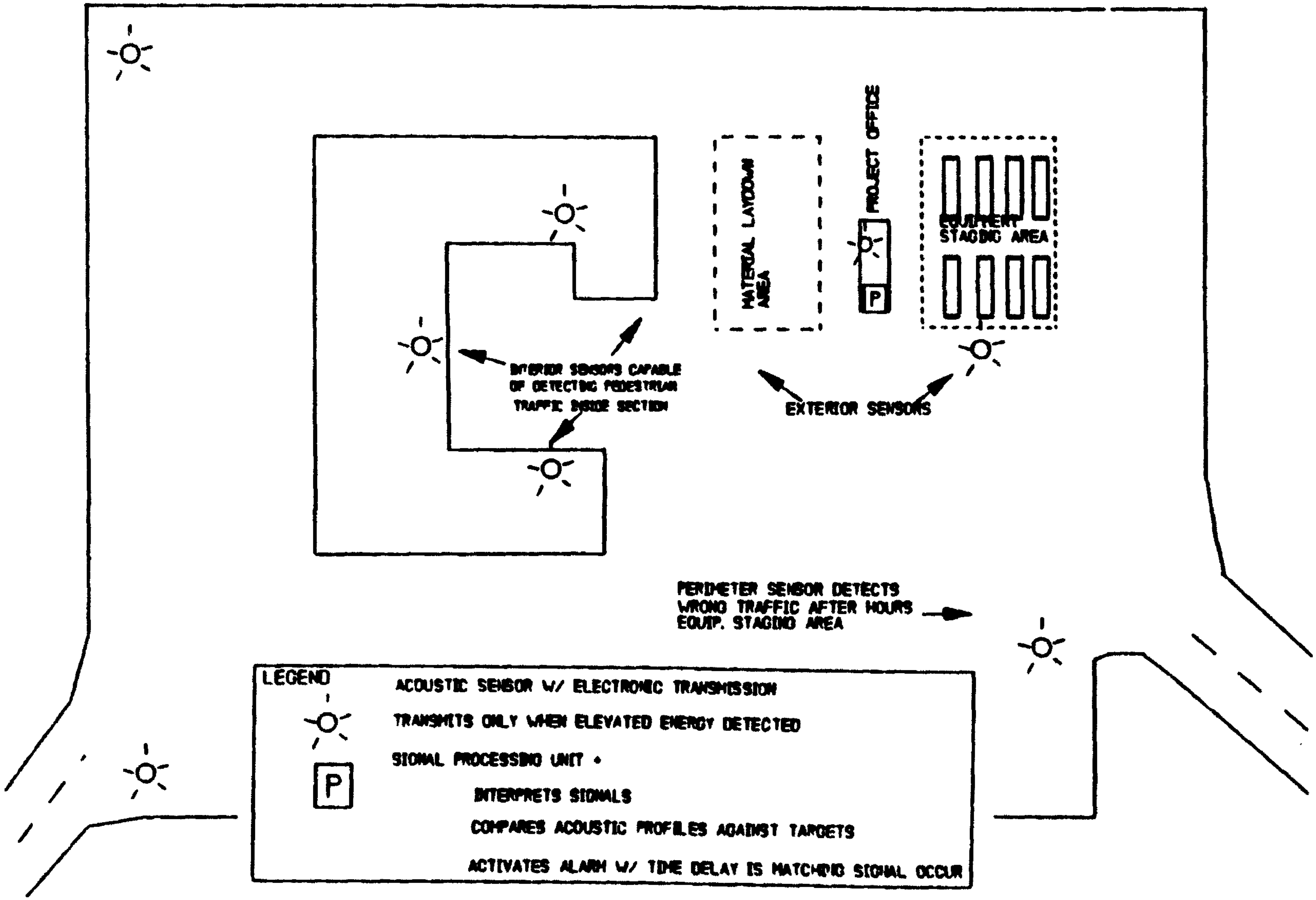


Figure 5.2 Application of Acoustic Sensing Technology as Passive Surviellance System

as technology improves. This $30K investment, however, could be recouped over a two-year period since the manpower normally devoted to manually compiling the same data could be reassigned to other activities.

Summary

While the preceding examples are not intended to provide an all inclusive representation of all possible construction applications of acoustic sensory technology, they demonstrate the versatility of such a system. As shown, one system could essentially be adapted for three different applications on the same job with minimal modification. Advantages of such an automated system are obvious;

- aside from initial capital costs, they require minimal operational costs
- the systems are portable and can be easily reconfigured
- they are unaffected by severe environmental conditions such as snow, mud, dust, and temperature swings
- they maintain steady level of vigilance over extended periods, subjected to repetitive operations

On the basis of the information presented, it is evident that acoustic sensory technology can be economically adapted to reduce or overcome a variety of vulnerabilities associated with construction operations.

CHAPTER 6

SUMMARY AND CONCLUSIONS

Overview

This final chapter compares the research conducted with the original objectives of the study. Problems observed and lessons learned during the study are also presented. The paper concludes with a discussion of areas for possible further research.

Comparison of Research with Objectives

As originally presented in chapter 1, accurate information gathering is a deficiency which currently exists in construction. In an effort to resolve this deficiency, researchers at several universities have been working years toward development of automated data acquisition systems to improve the quality of information obtained and reduce the cost of gathering it. This study demonstrates the feasibility of using acoustic sensory technology as a viable means of automated data collection for construction applications.

Three objectives were established for demonstrating the viability of such sensory systems.

1. Data Collection. In order to demonstrate feasibility of acoustic interpretation of signals, data had to first be collected under field conditions using reliable, yet readily available recording equipment. This was accomplished by recording construction

operations by means of a video recorder positioned at a stationary site along construction haul routes at three project sites.

2. Data Analysis. Once collected, data had to be analyzed to determine if sufficient differences existed in acoustic signatures to permit distinction among different types of equipment. This objective was accomplished by analyzing 68 separate samples through a digital signal processor and analyzing results. Two forms of signal analysis were performed: spectral and spectrographic analysis. Results obtained confirmed that key acoustic features varied sufficiently among types of equipment to permit positive identification of the source. Results further indicated that spectral differences in acoustic profiles could be used to determine if haul units were loaded or empty.

3. Applications. The final objective of the research was to demonstrate real world applications where acoustic sensory technology could be applied to resolve likely problems. Three applications were suggested. The first addressed use of acoustics sensory technology for productivity measurement and control on equipment intensive operations. The second addressed traffic control implications on hauling operations. The third proposed acoustic sensory technology as a means of passive surveillance of construction sites.

Limitations of Study/Lessons Learned

While results of the study indicate that acoustic sensory technology is both feasible and potentially applicable to real world problems, it is important to note that the research was preliminary in nature and limited in several respects.

First, the study was limited to identification of acoustic features in a qualitative manner, not definitive manner. This was due to fact that number of acoustic samples studied were insufficient to draw conclusions with absolute certainty about the equipments' acoustic profiles. The limited acoustics expertise possessed by the author in studying this application to civil engineering problems also precluded definitive resolution. Much more rigorous analysis is required to determine features capable of definitively describing the acoustic signature of a given type of equipment.

Second, the study failed to investigate the effect of vehicle age, speed, and terrain had on the acoustic profiles generated.

Third, acoustic samples for this preliminary study were recorded only under favorable temperature and weather conditions. This was done to minimize the variability of data. It was necessary to prove the correlation between production related sounds and specific types of equipment prior to factoring in variations in temperature and weather. These conditions are known to affect the acoustic profile, but not to what degree. This aspect needs to be investigated.

Fourth, the study did not address the effects caused when multiple vehicles are recorded simultaneously. One such incident arose during data collection phase where two 50 ton dump trucks, one loaded and one empty, passed the recording station simultaneously, producing a composite acoustic signature. Since no known means were available to separate the component sounds of each, the sample was eliminated from this study. Future research should however focus on development of a means to

separate the components of multiple vehicles so that each can be individually identified.

Last, the recording equipment used in this preliminary study was found to be inadequate to capture sounds over the very low frequencies (100 hz and below). Harmonic features within this range offer a great deal of information about the equipment under study. While the use of a camcorder is an ideal piece of recording equipment for research related to construction equipment sounds, future recording efforts may need to utilize a separate high resolution microphone with wind screen to permit capture of these low frequency spectral features.

Recommendations for Further Research

In order to exploit the potential of acoustic sensing as an information gathering tool for construction as well as a variety of other applications, follow-up research is recommended in a number of areas.

In the immediate future, in-depth acoustic analysis needs to be initiated on numerous samples of construction equipment to definitively identify their acoustic traits. Within this realm, acoustic researchers need to investigate and determine the quantitative effects of temperature, weather, terrain, and vehicle speed on the resultant acoustic profiles. Researchers may also want to consider patterning such sounds as pedestrian traffic, opening of doors, and human voices in order to assist with development of passive acoustic surveillance systems. From this research, a comprehensive acoustic data base needs to be established, presented in the form of

a set of rules or heuristics which facilitate identification of the source.

Using these rules, research is then needed within the signal processing or computer science disciplines to develop a program capable of automatically determining the sound source through acoustic pattern recognition.

In order to transform the idea of acoustic sensory technology into a workable end-product, developmental research is needed in the field of electrical engineering. The main objective of the research in this area would be to develop a remote acoustic sensing devise capable of working under a wide range of temperature conditions while satisfying the requirements of portability. Such a sensing device would have to be compact, wireless, and capable of transmitting the signal to the processing station in real-time. Such sensors are needed due to the frequent reconfiguration of construction operations.

Conclusions

This study, intended as exploratory research into the problem of information gathering, demonstrated that passive acoustics monitoring is a feasible means of data collection in the construction environment.

From this study, it was proven that different types of construction equipment can be readily distinguished based upon their acoustic signatures. It was also proven that a load status determination can be made based upon spectral differences in the profiles of loaded and empty equipment. This finding demonstrated the feasibility of

acoustic sensing as a data acquisition tool for equipment intensive operations. Development of technology to exploit this knowledge could potentially improve decision making and production control from a construction manager's perspective.

Two other applications of acoustic sensing related to construction were also proposed, following the assumption that through signal analysis, other signals in addition to construction equipment could be readily identified and cataloged.

In short, results of this study indicate that passive acoustic monitoring can be used effectively as an information gathering tool in the construction environment. Additional research is, however, needed to adapt the system to operate under real world conditions. The following actions are needed:

- development of a reliable database of acoustic samples
- develop of programming logic to process, interpret, and act upon signals in a real-time environment
- development of remote sensory equipment, impervious to weather conditions

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Appendix A.: SPECTRAL PROFILE

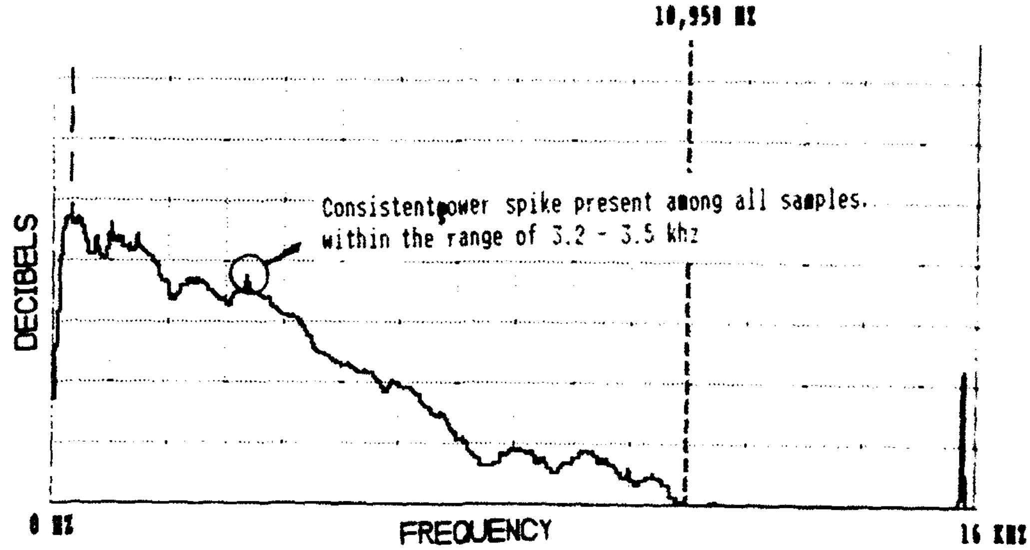

FIGURE A.1: Power Spectrum Profile Representative of Loaded CAT 627E Scraper

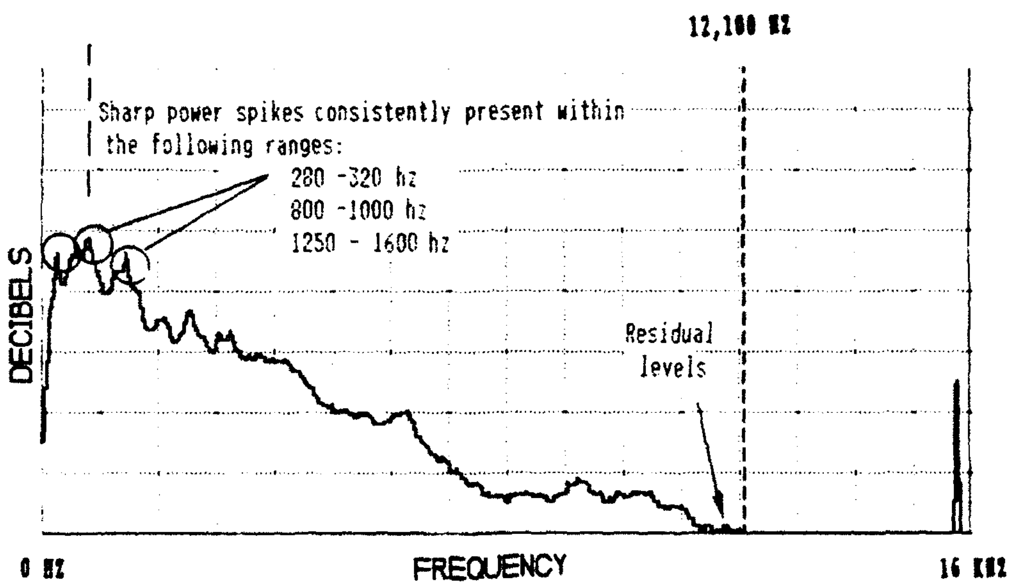

FIGURE A.2: Power Spectrum Profile Representative of Empty CAT 627E Scraper

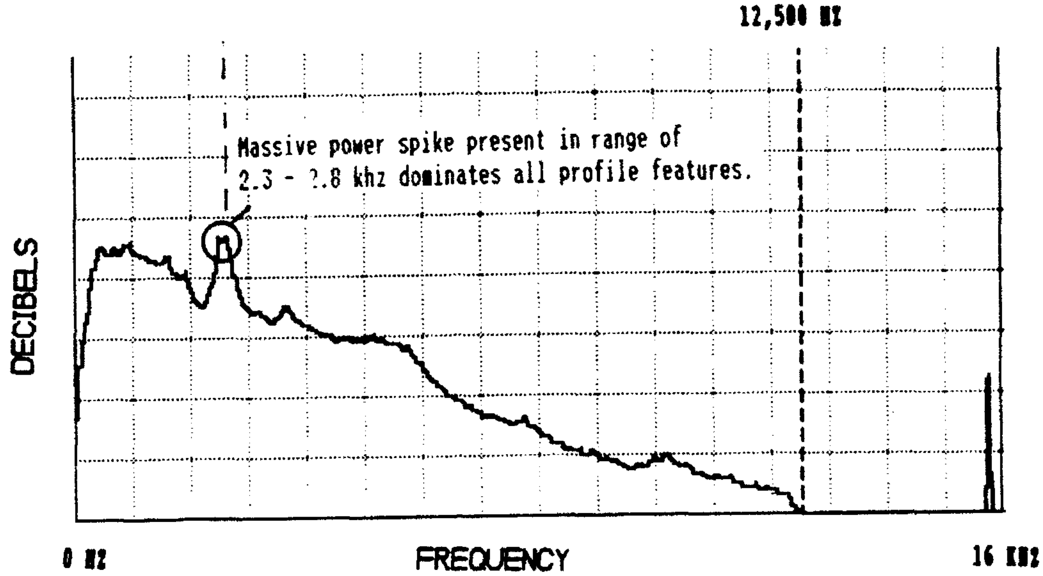

FIGURE A.3: Power Spectrum Profile Representative of Loaded 50 Ton Euclid Dump Truck

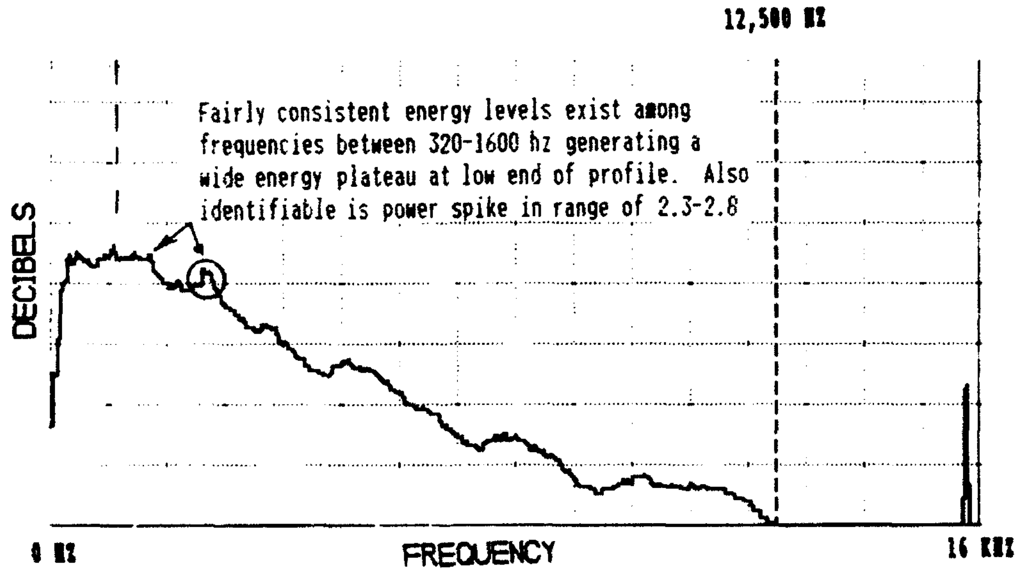

FIGURE A.4: Power Spectrum Profile Representative of Empty 50 Ton Euclid Dump Truck

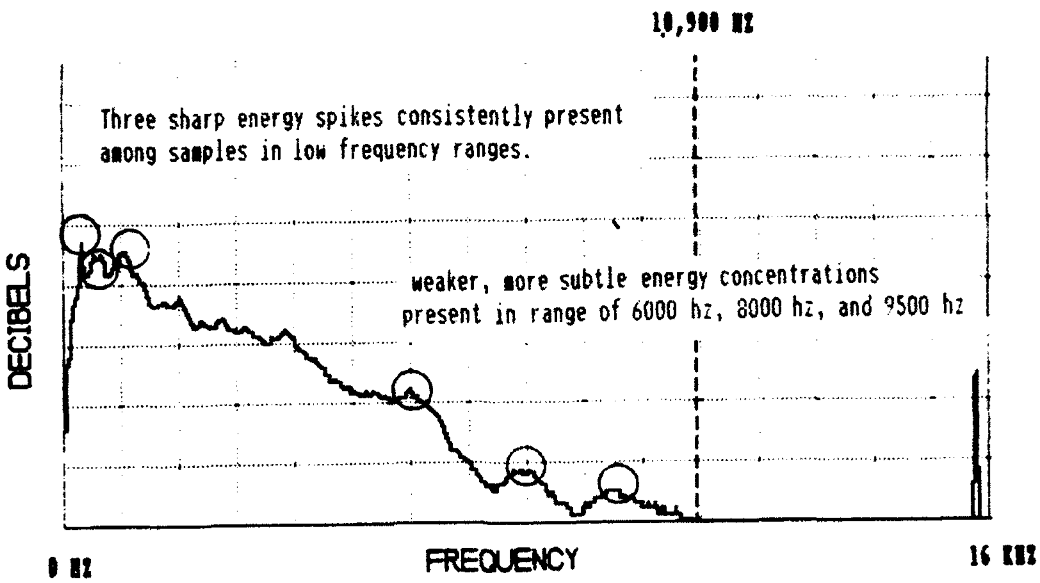

FIGURE A.5: Power Spectrum Profile Representative of Loaded 75 Ton Euclid Dump Truck

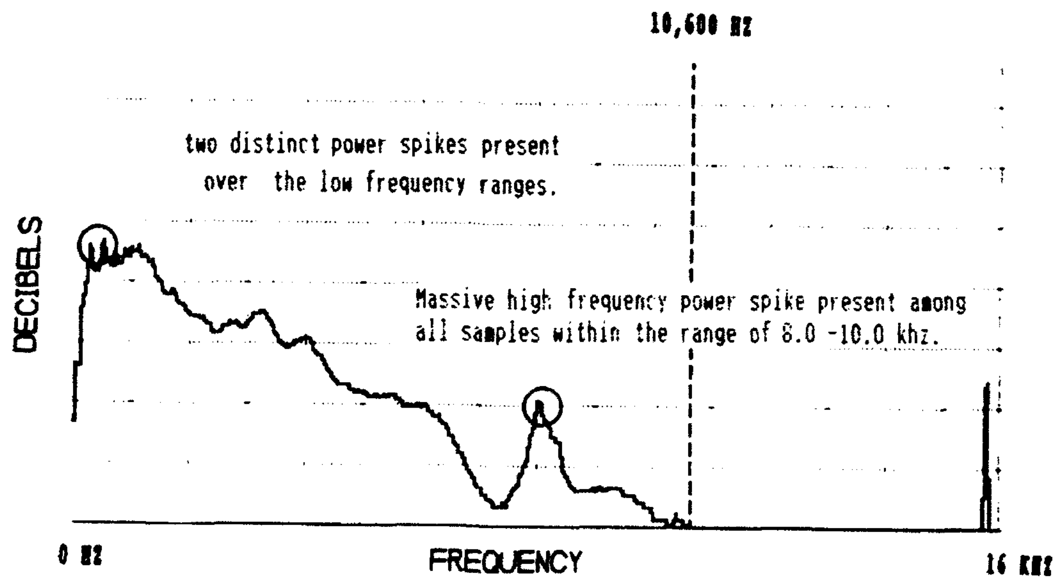

FIGURE A.6: Power Spectrum Profile Representative of Empty 75 Ton Euclid Dump Truck

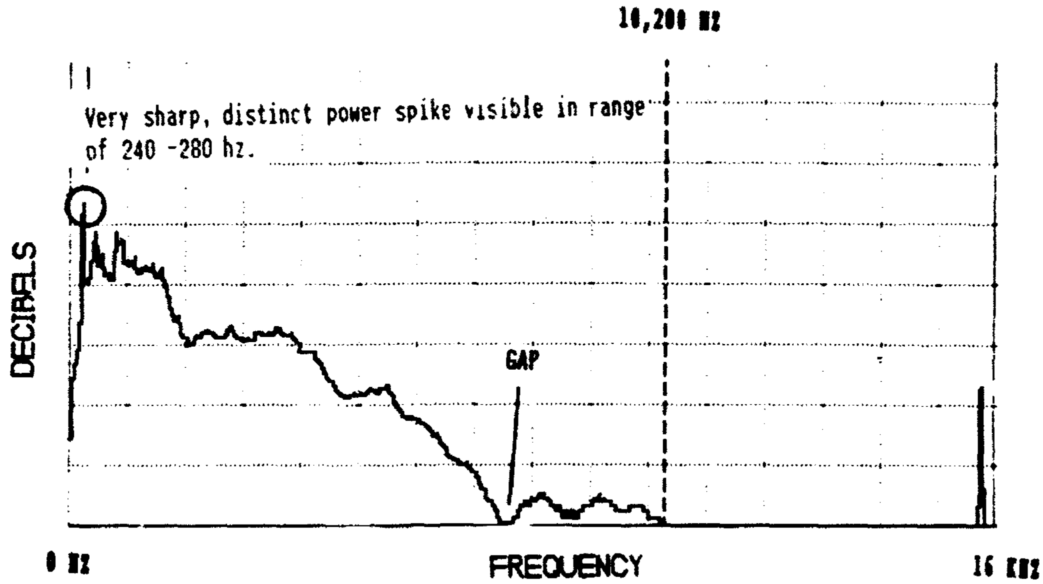

FIGURE A.7: Power Spectrum Profile Representative of Mack 6200 Gallon Water Truck

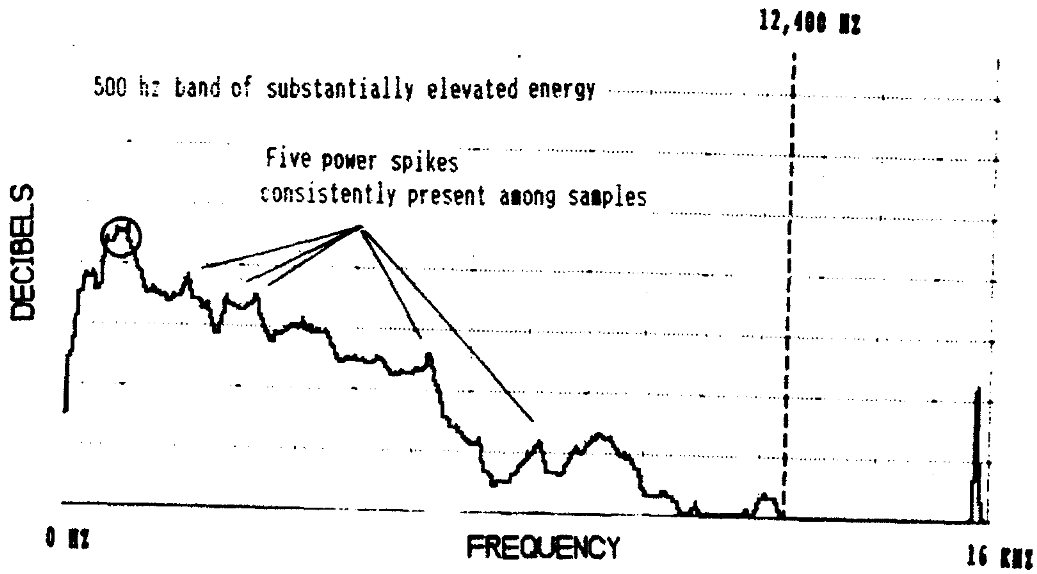

FIGURE A.8: Power Spectrum Profile Representative of CAT D8N Bulldozer

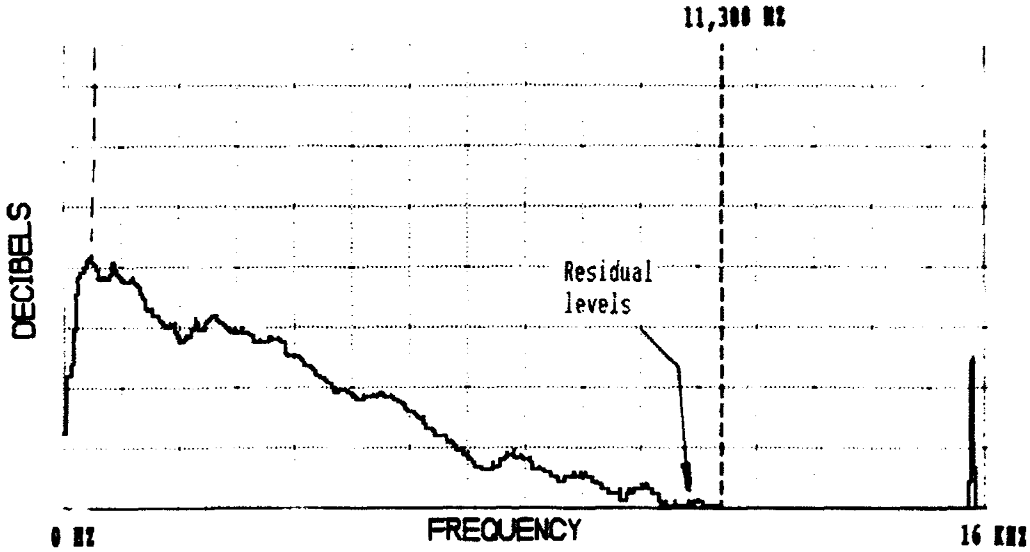

FIGURE A.9: Power Spectrum Profile Representative of Ford F-150 Pick-up Truck

Appendix B.
0 - 2 khz SPECTROGRAPHIC PROFILE

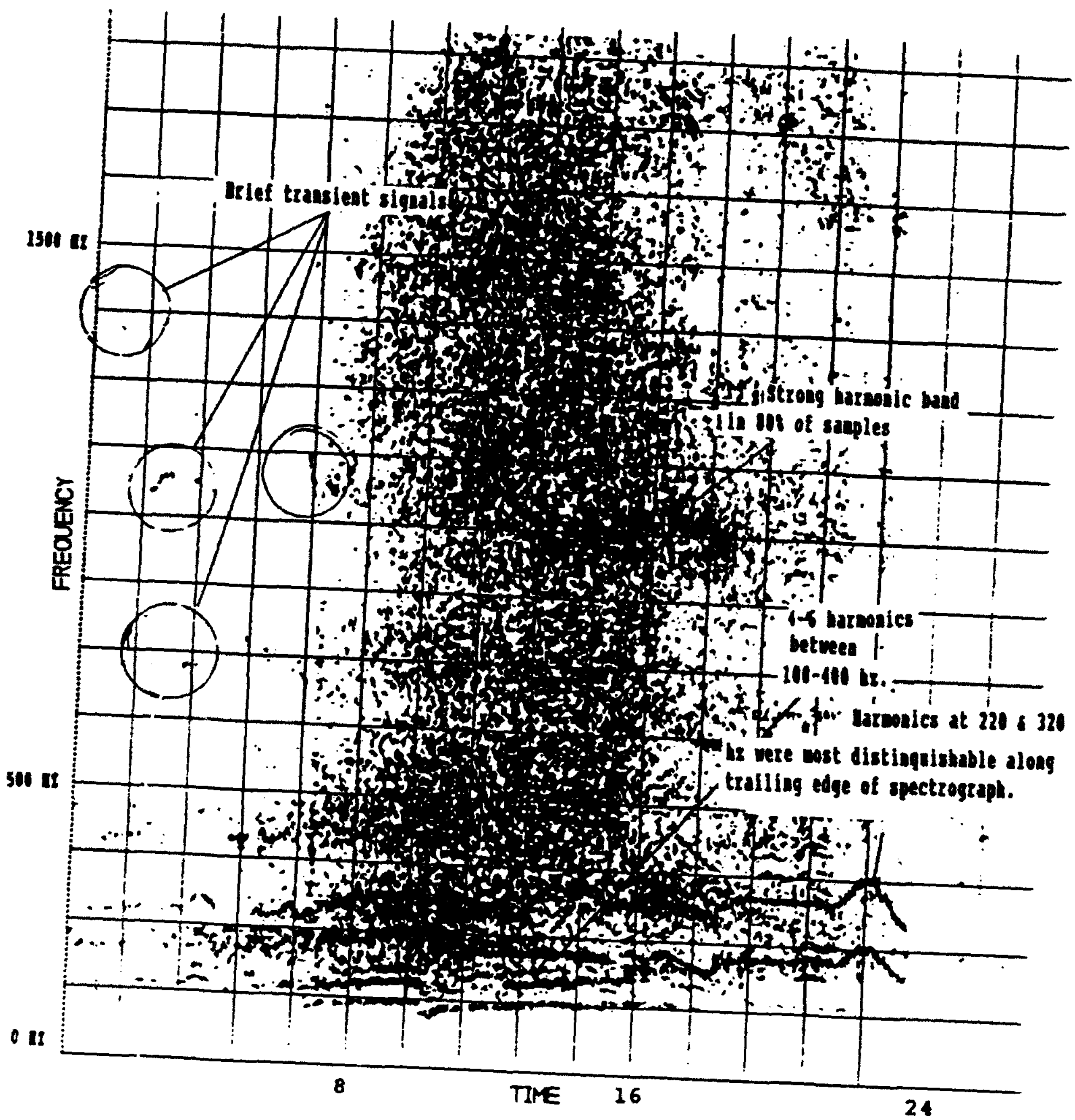

FIGURE B.1: **DC - 2 khz Spectrograph Representative of Loaded CAT Scraper**

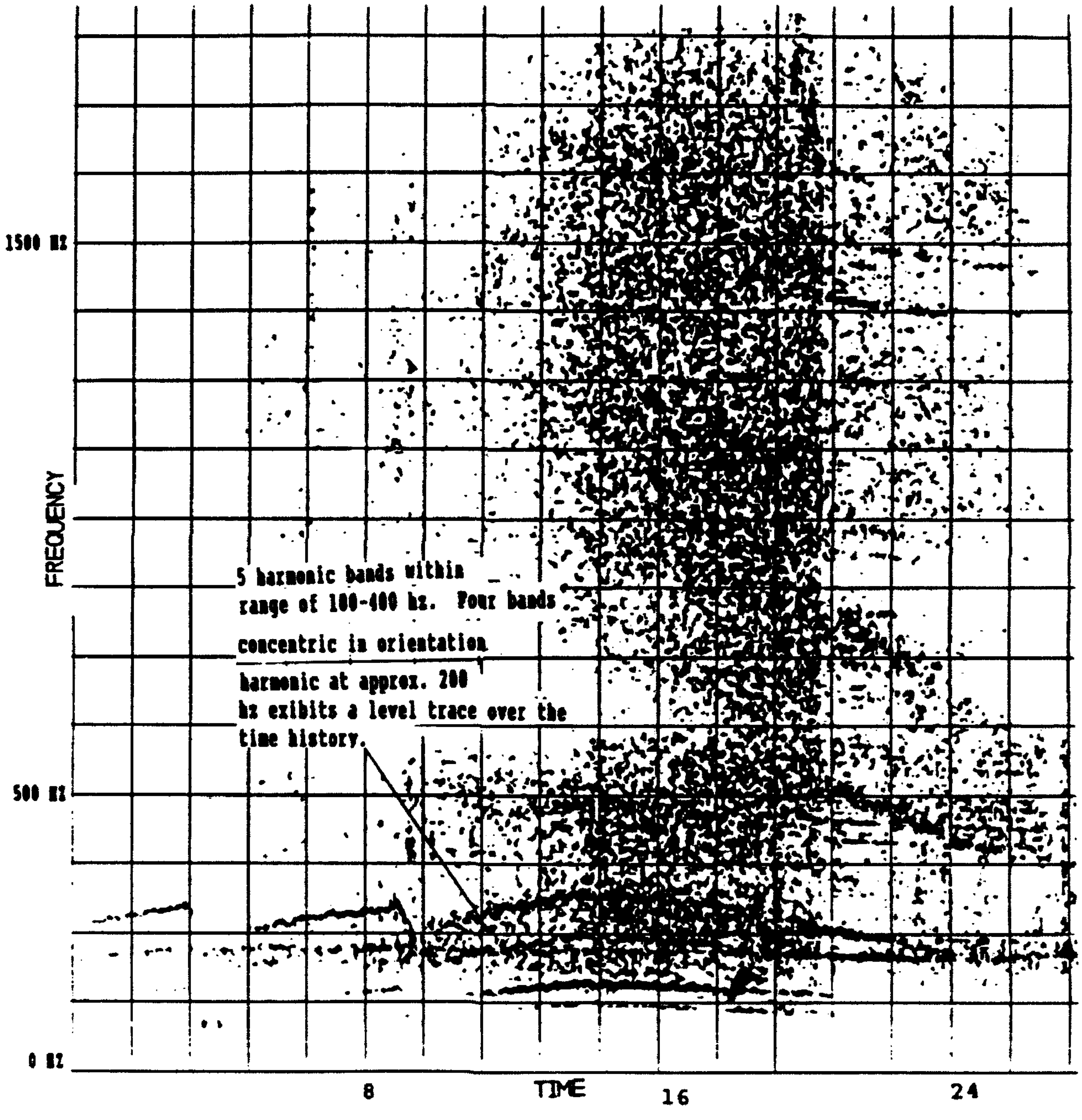

FIGURE B.2: DC - 2 khz Spectrograph Representative of Empty CAT Scraper

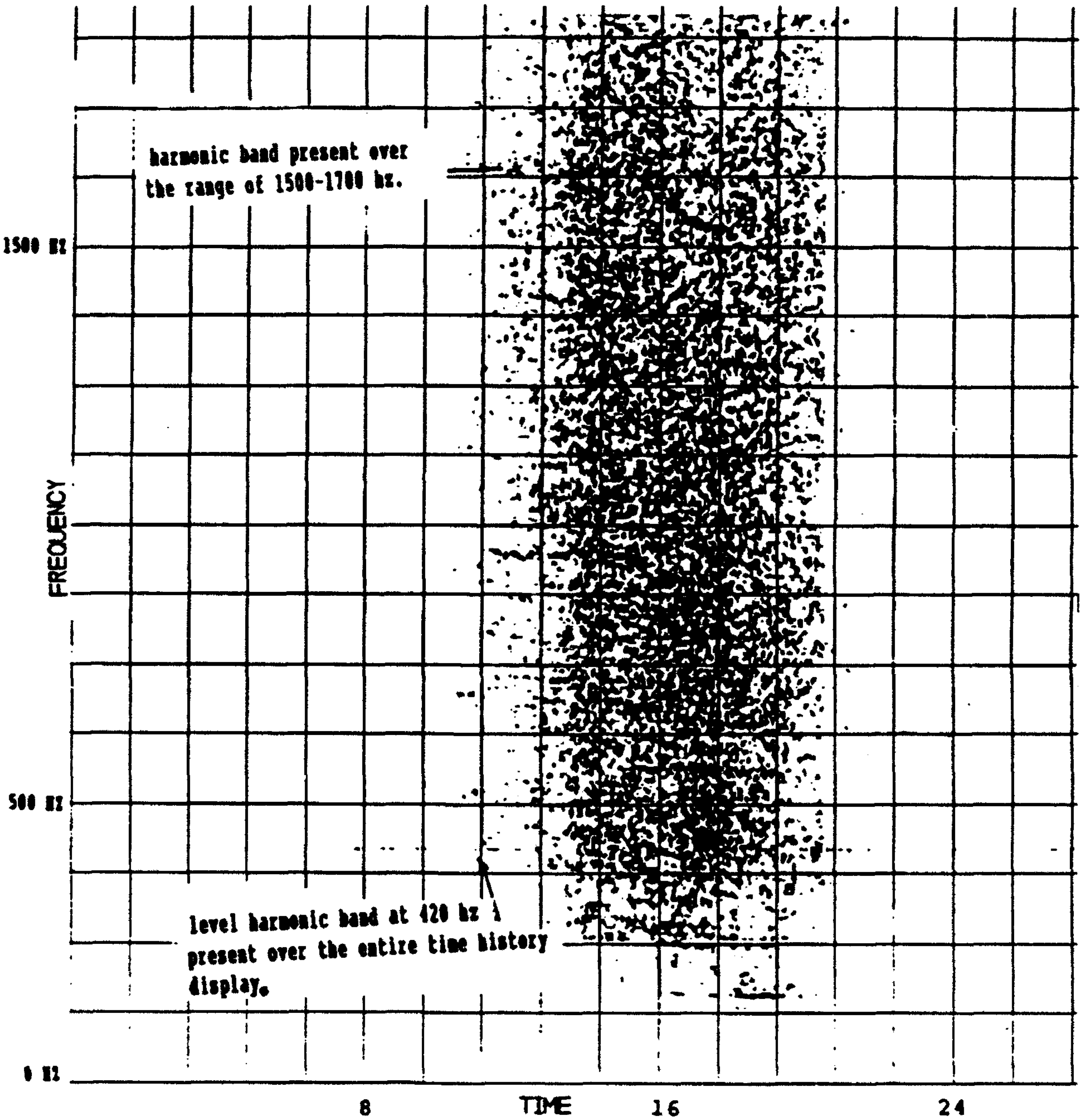

FIGURE B.3: DC - 2 khz Spectrograph Representative of Loaded 50 Ton Euclid Dump Truck

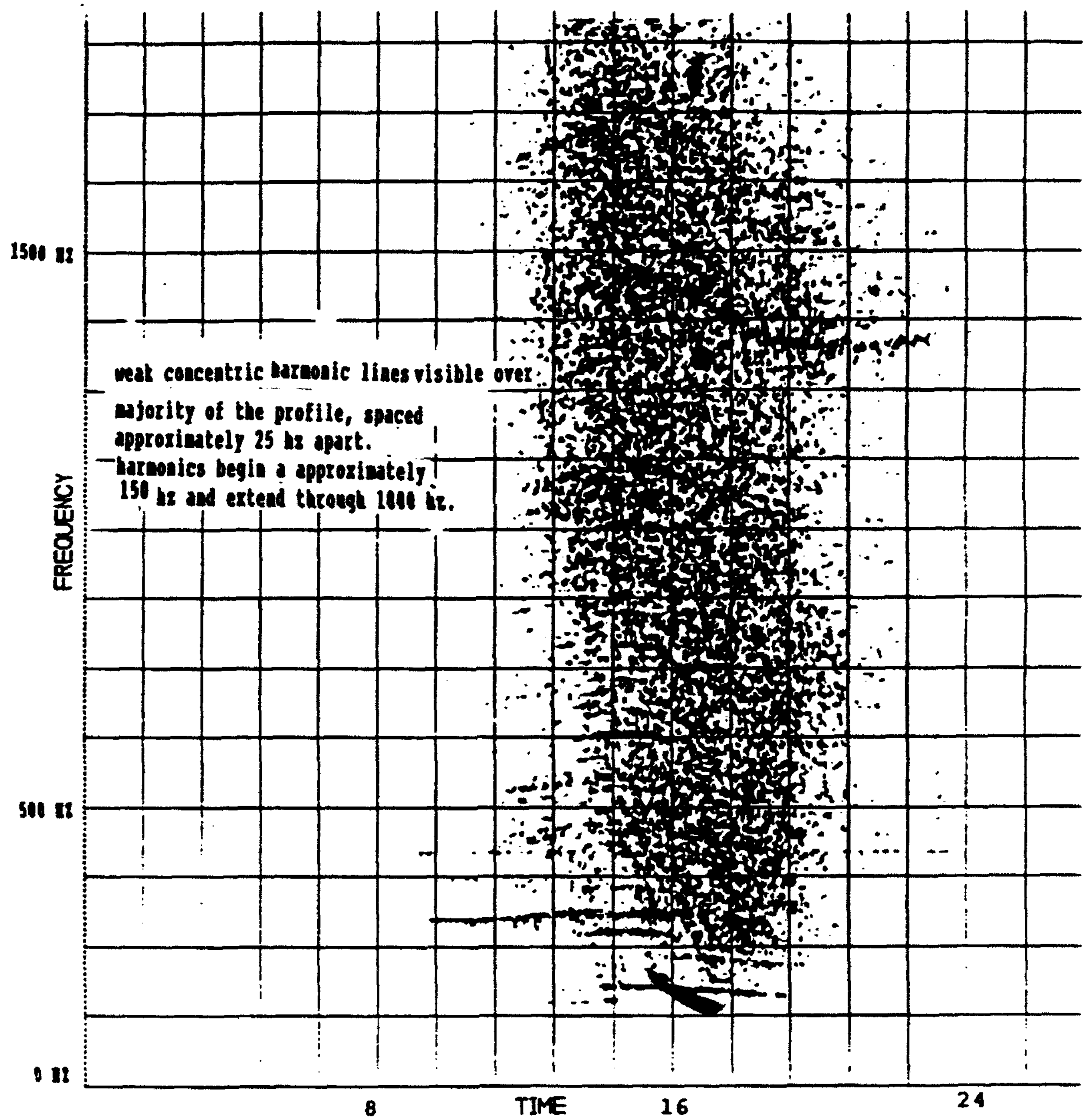

FIGURE B.4: DC - 2 khz Spectrograph Representative of Empty 50 Ton Euclid Dump Truck

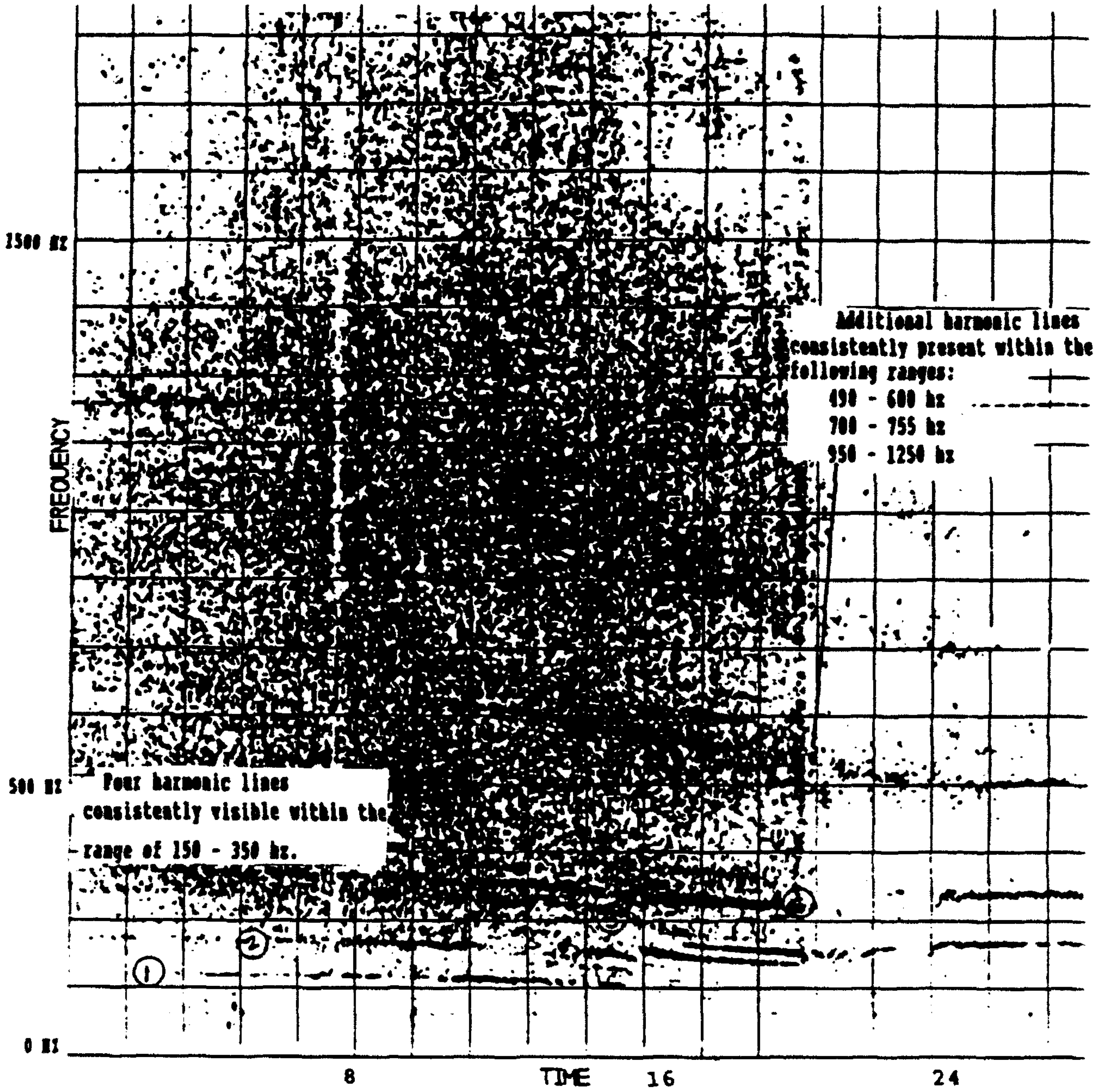

FIGURE B.5: DC - 2 khz Spectrograph Representative of Loaded 75 Ton Euclid Dump Truck

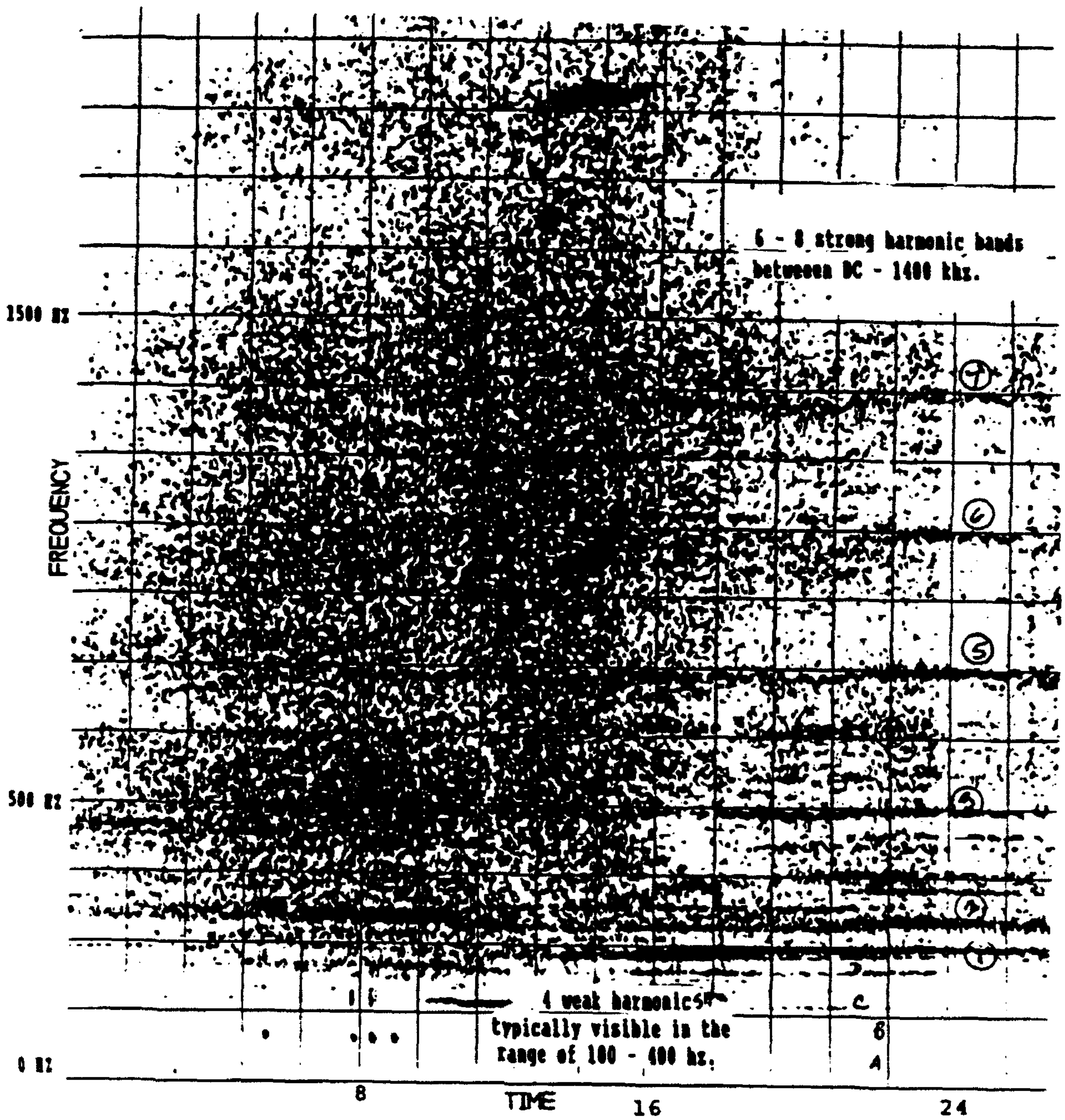

FIGURE B.6: DC - 2 khz Spectrograph Representative of Empty 75 Ton Euclid Dump Truck

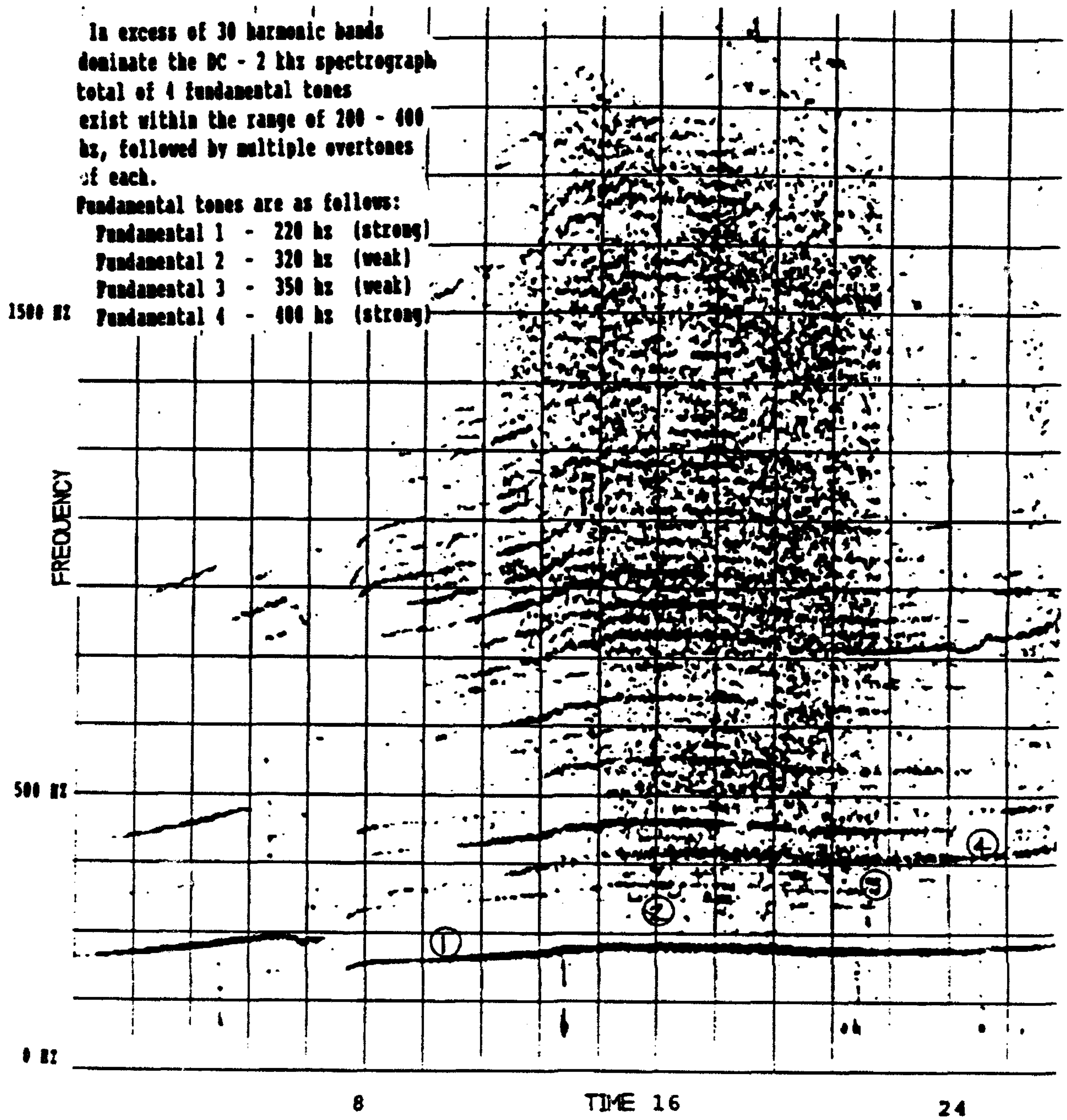

FIGURE B.7: DC - 2 khz Spectrograph Representative of Mack 6200 Gallon Water Truck

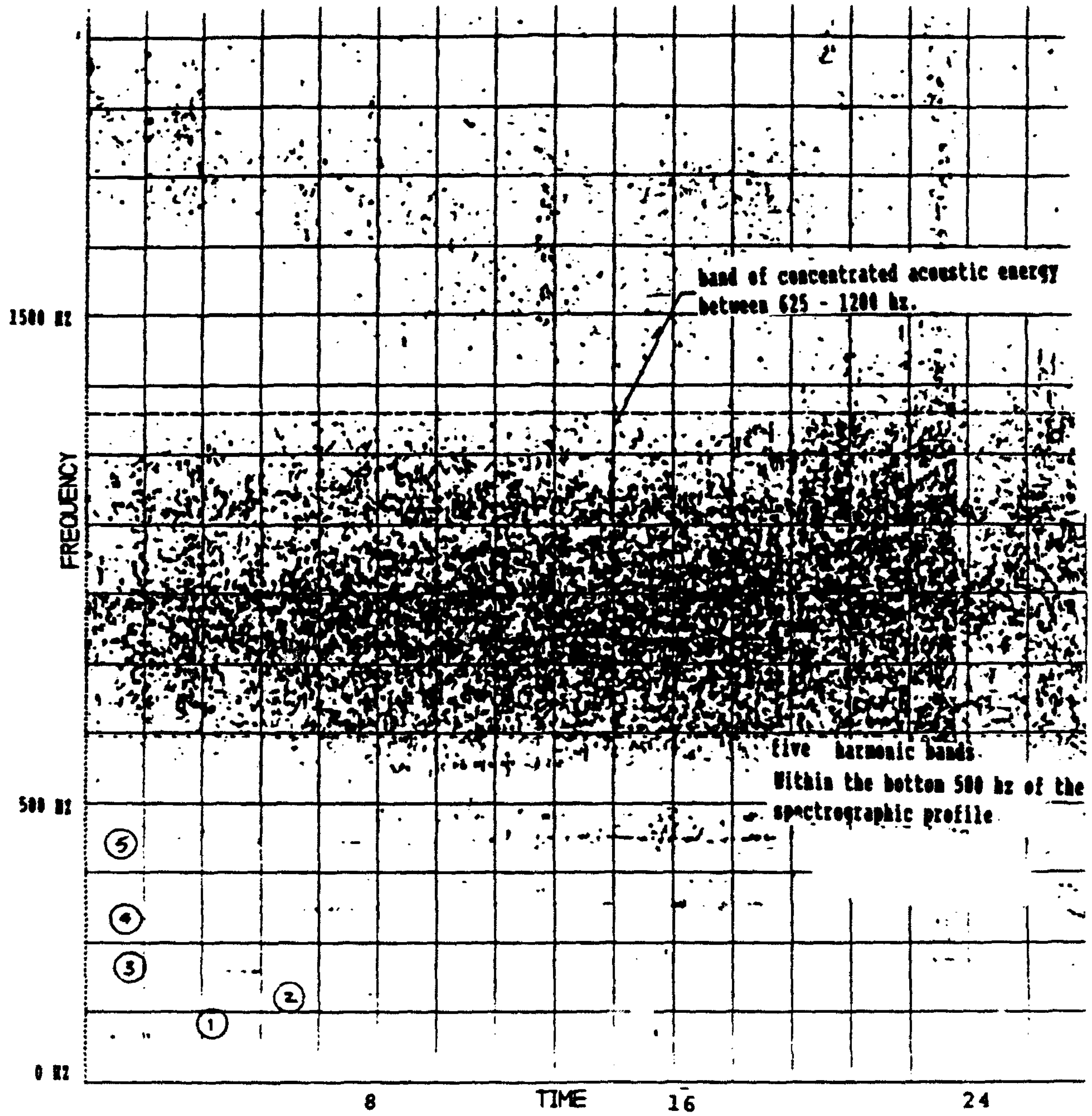

FIGURE B.8: DC - 2 khz Spectrograph Representative of CAT D8N Bulldozer

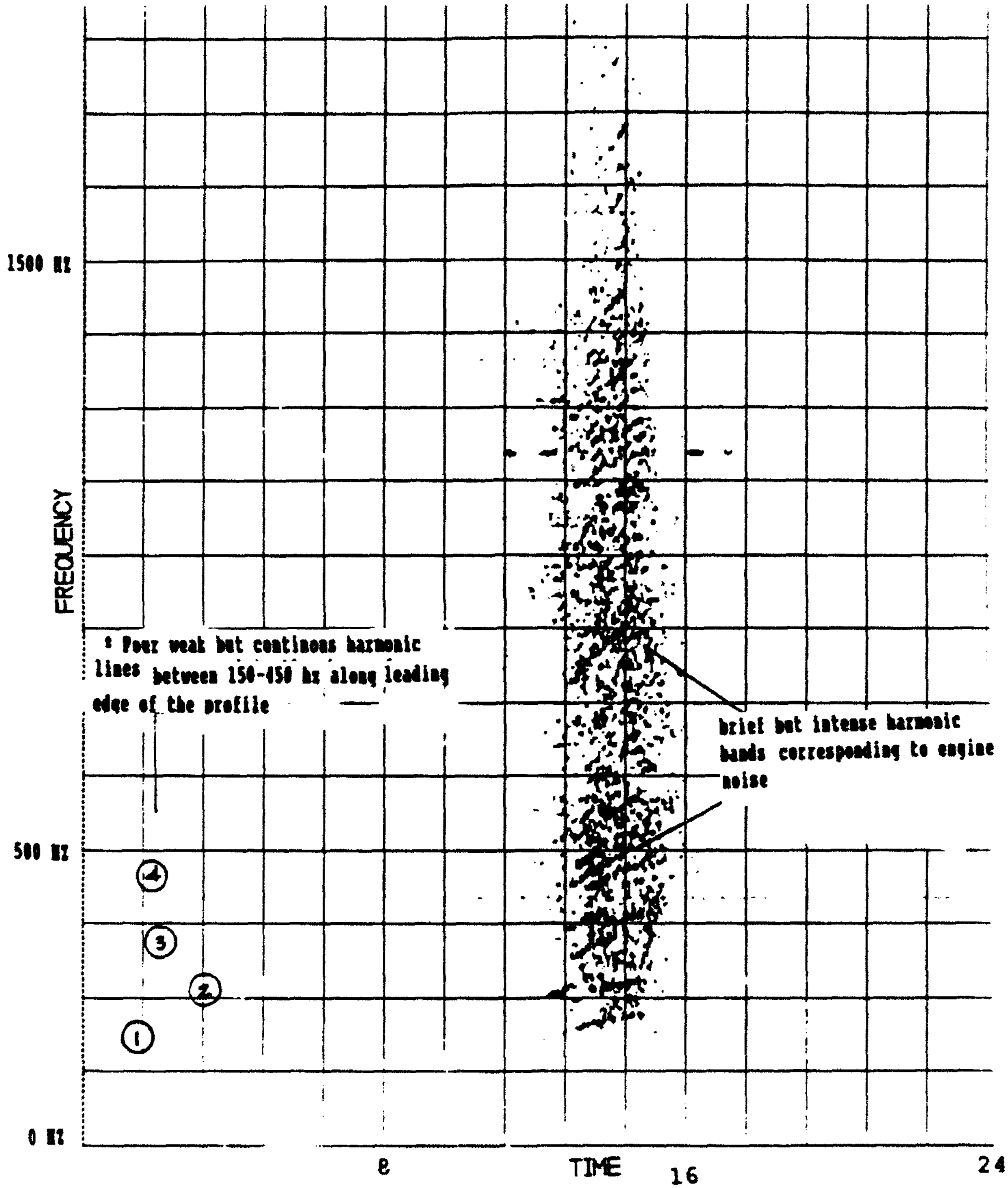

FIGURE B.9: DC - 2 khz Spectrograph Representative of Ford F-150 Pick-up Truck

Appendix C.
0 - 8 khz SPECTROGRAPHIC PROFILE

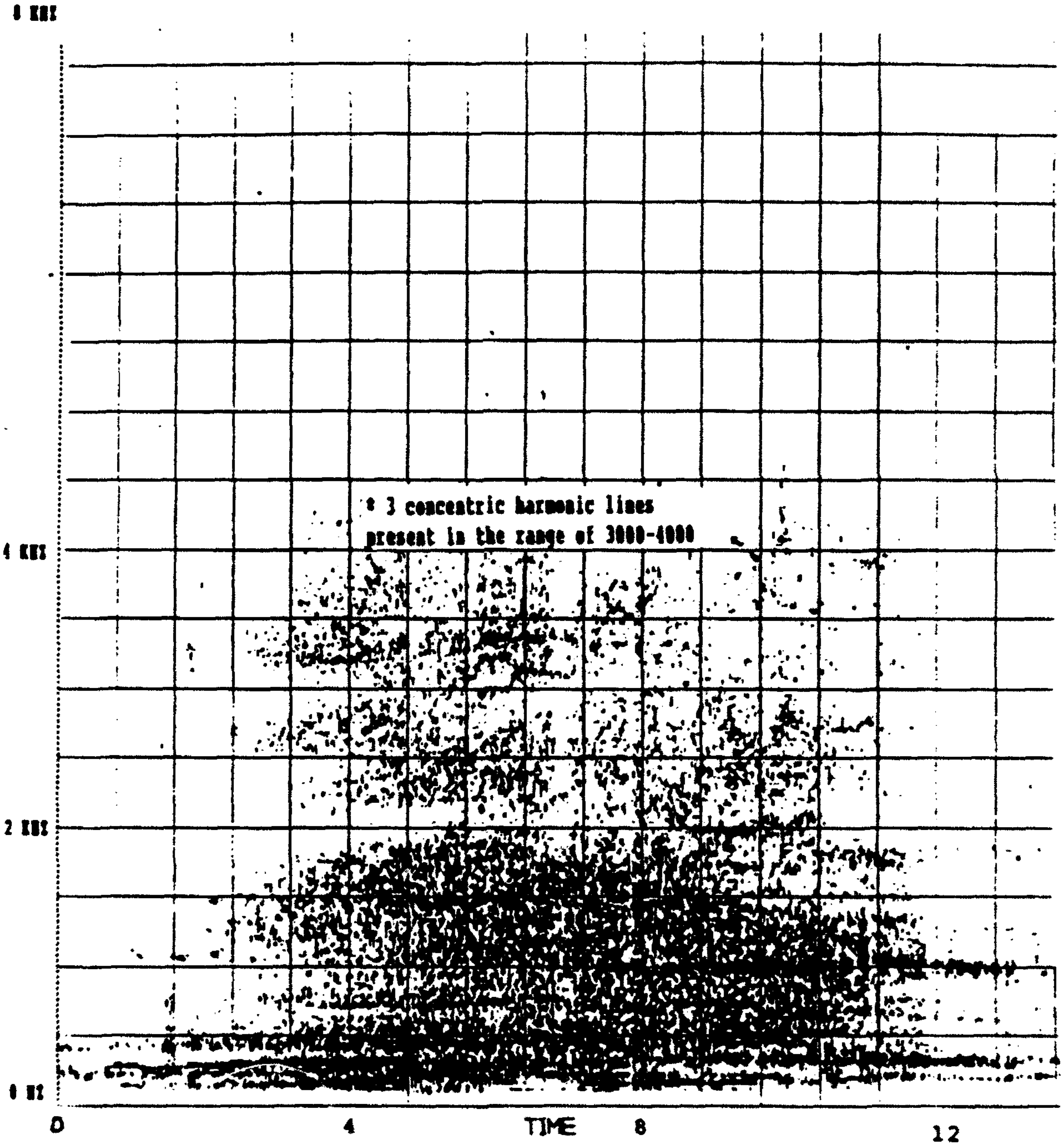

FIGURE C.1: DC - 8 khz Spectrograph Representative of Loaded CAT Scraper

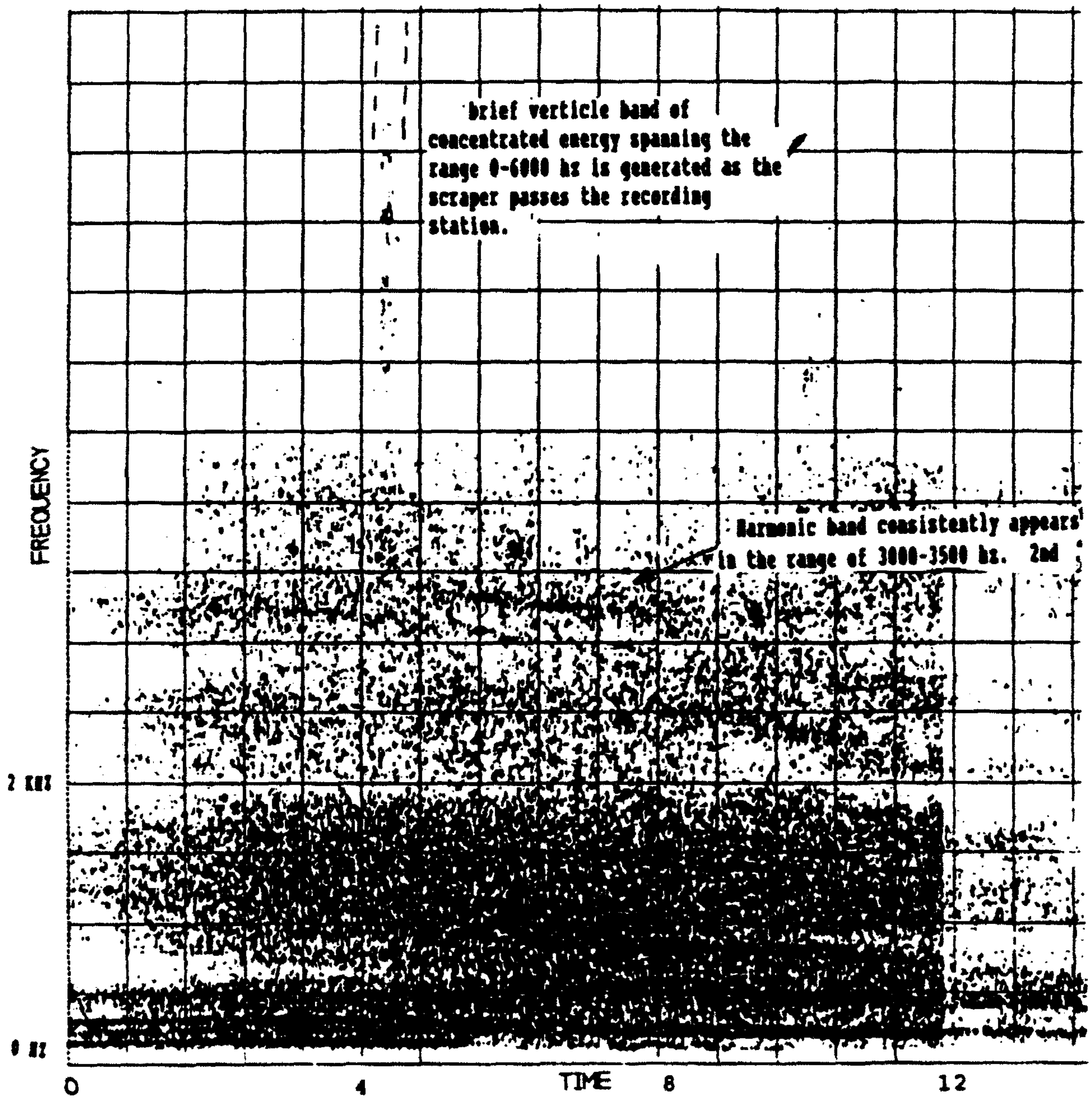

FIGURE C.2: DC - 8 khz Spectrograph Representative of Empty CAT Scraper

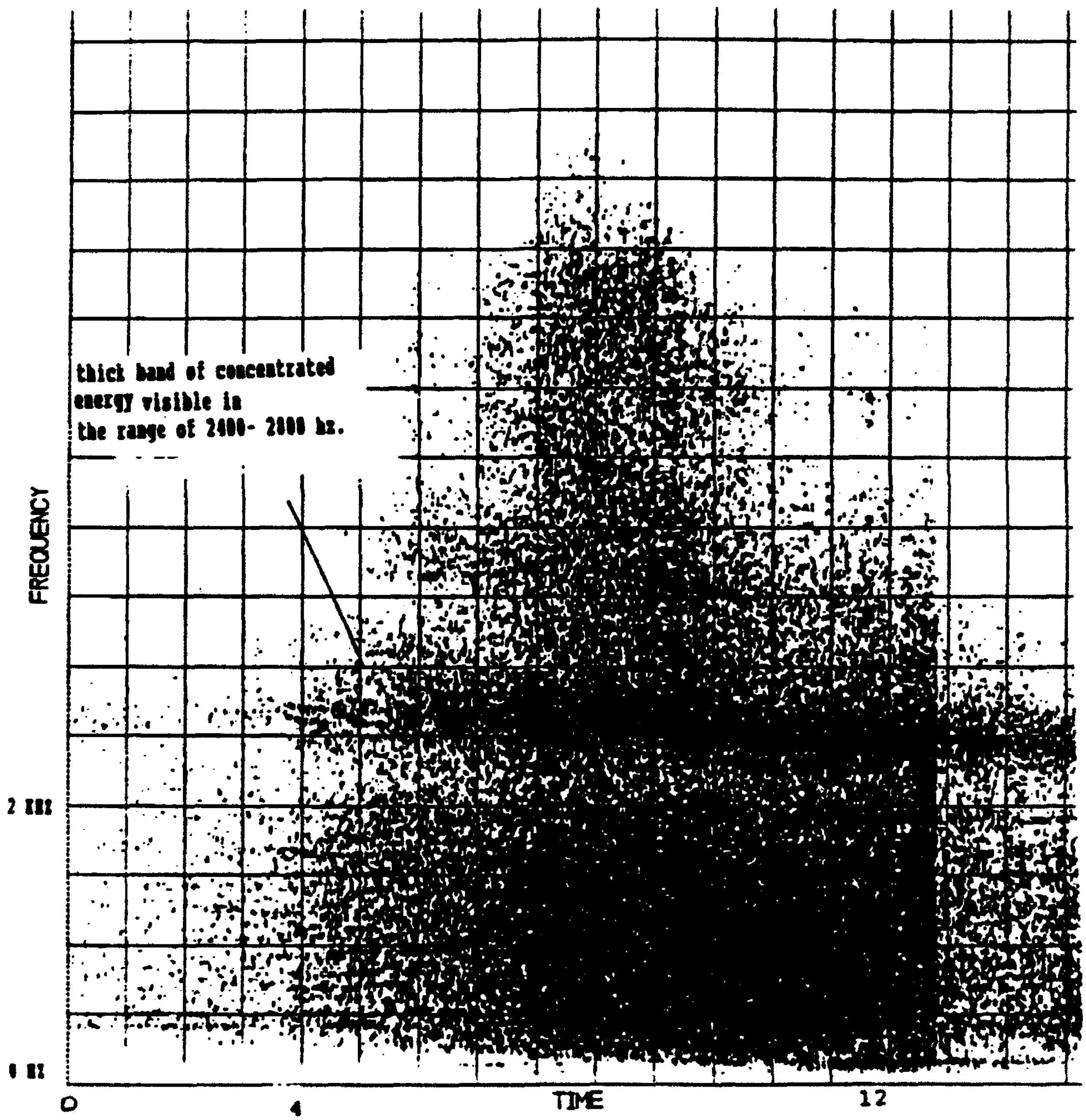

FIGURE C.3: DC - 8 khz Spectrograph Representative of Loaded 50 Ton Euclid Dump Truck

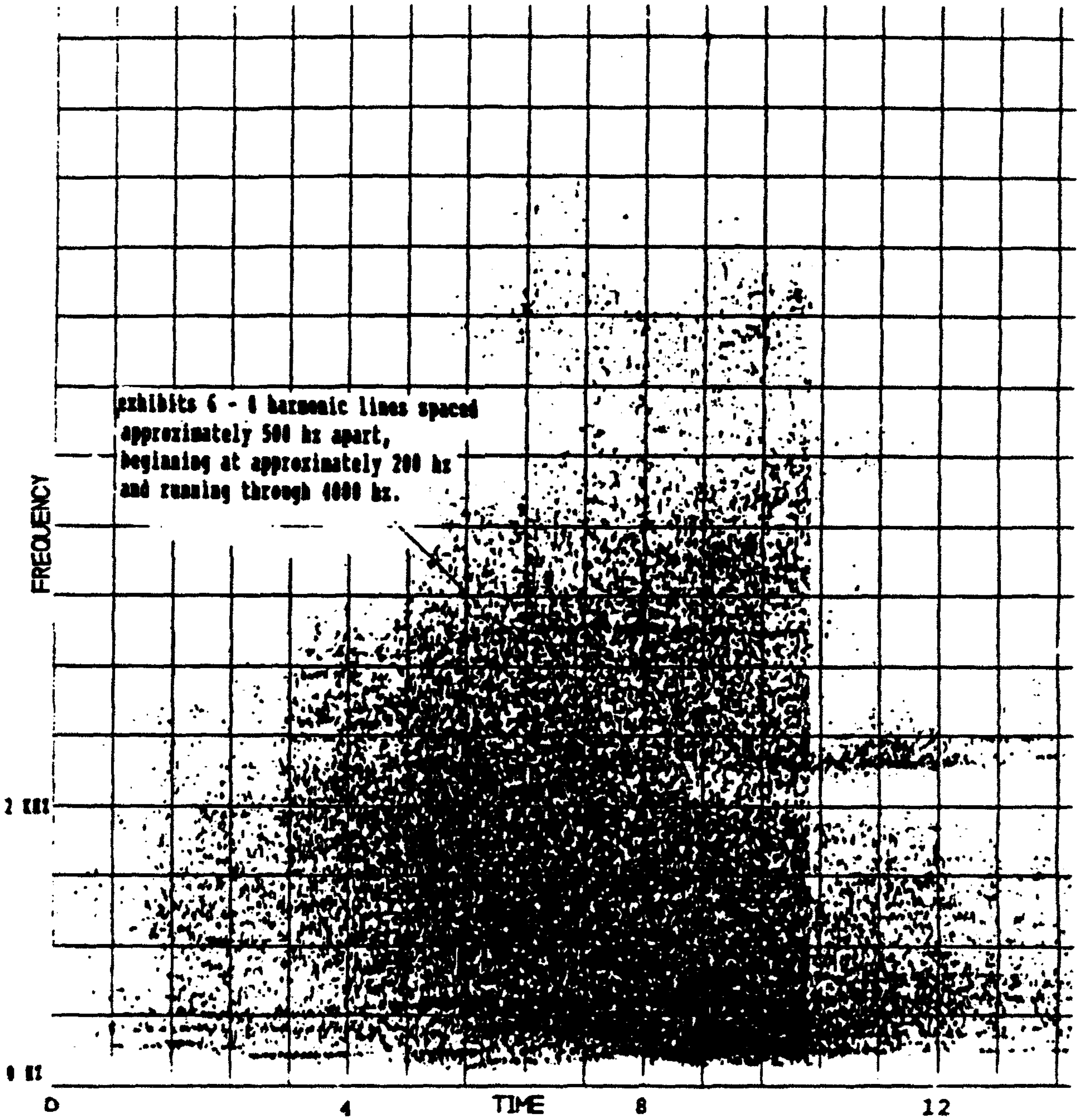

FIGURE C.4: DC - 8 khz Spectrograph Representative of Empty 50 Ton Euclid Dump Truck

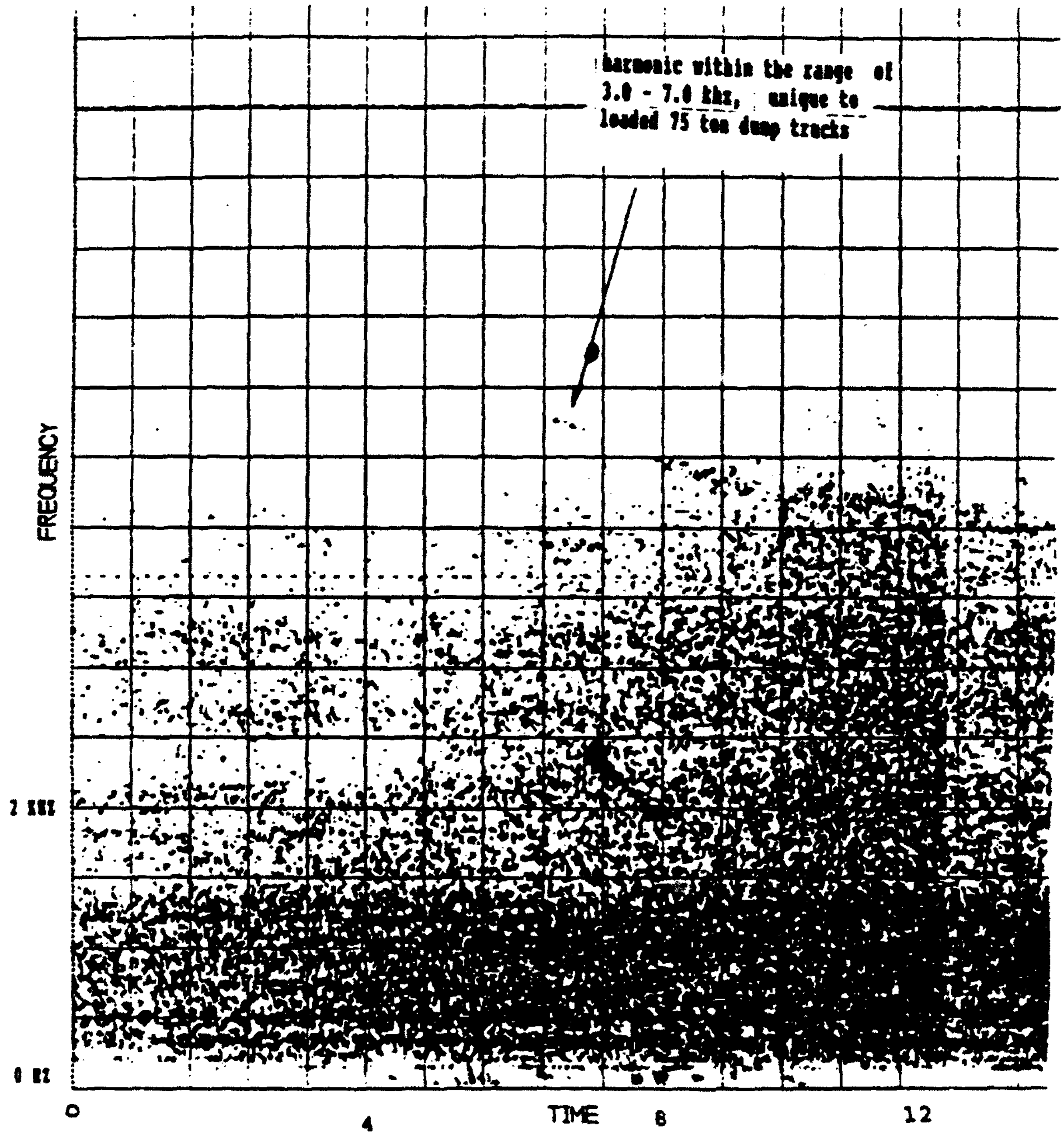

FIGURE C.5: DC - 8 khz Spectrograph Representative of Loaded 75 Ton Euclid Dump Truck

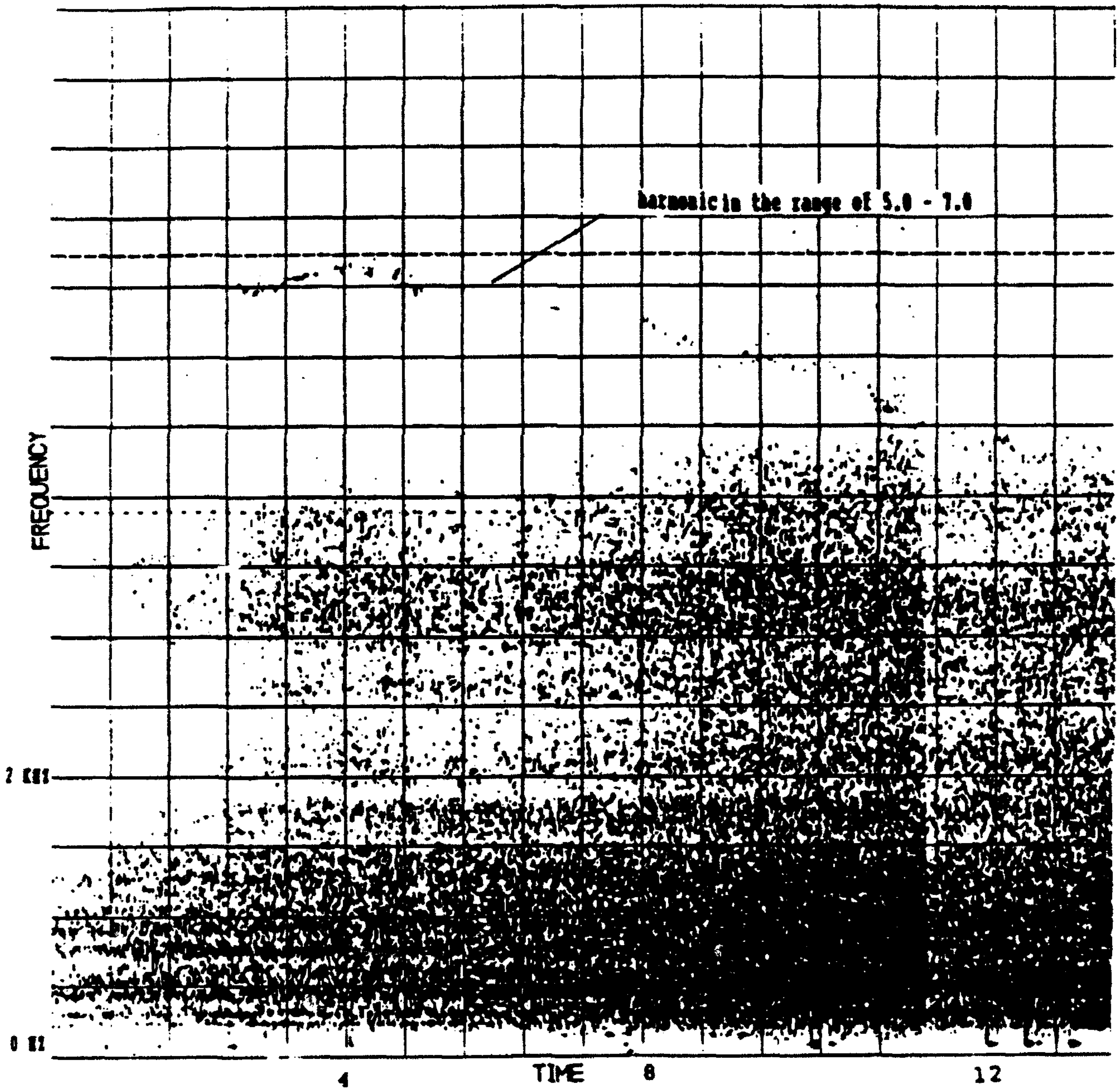

FIGURE C.6: DC - 8 khz Spectrograph Representative of Empty 75 Ton Euclid Dump Truck

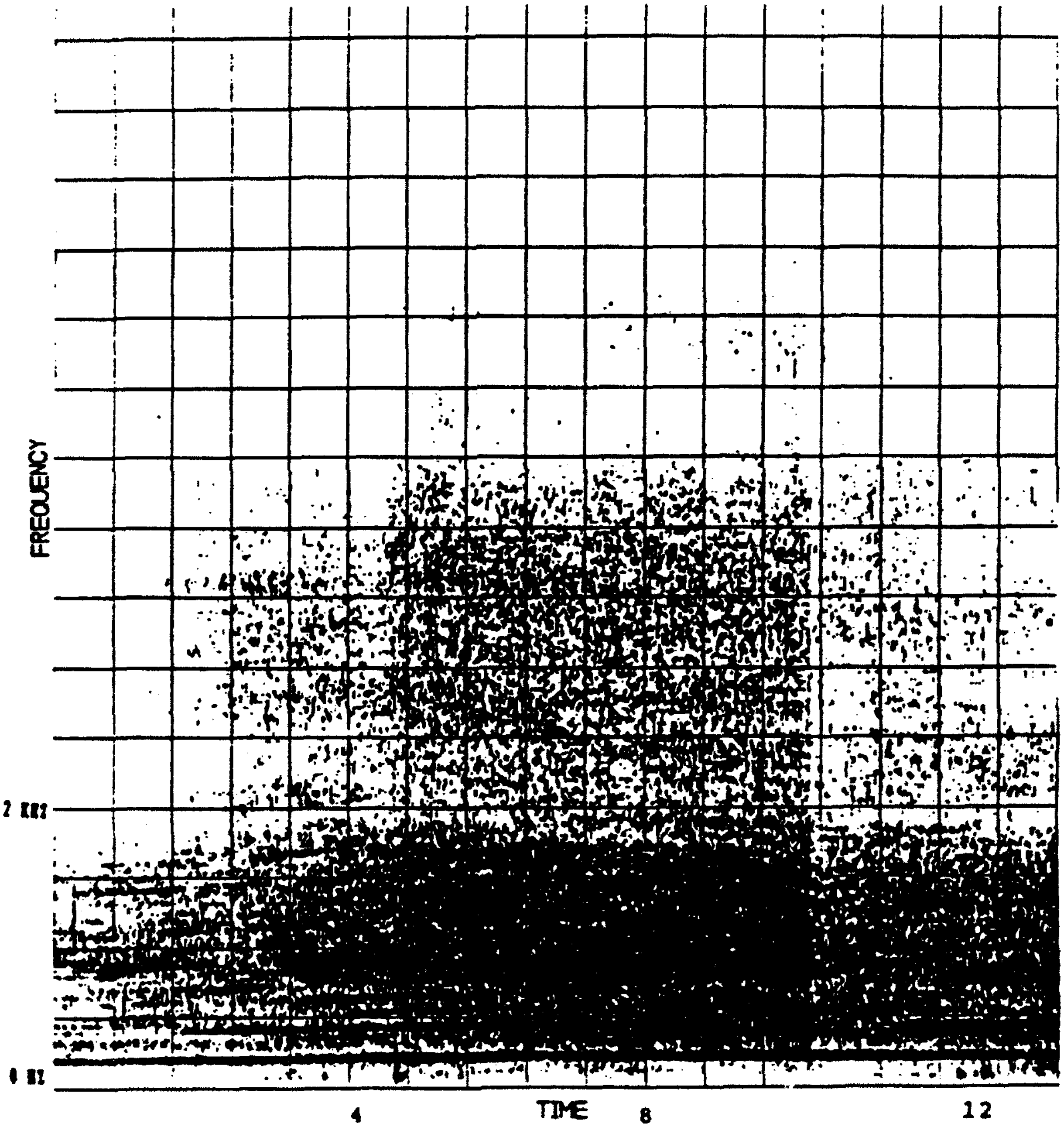

FIGURE C.7: DC - 8 khz Spectrograph Representative of Mack 6200 Gallon Water Truck

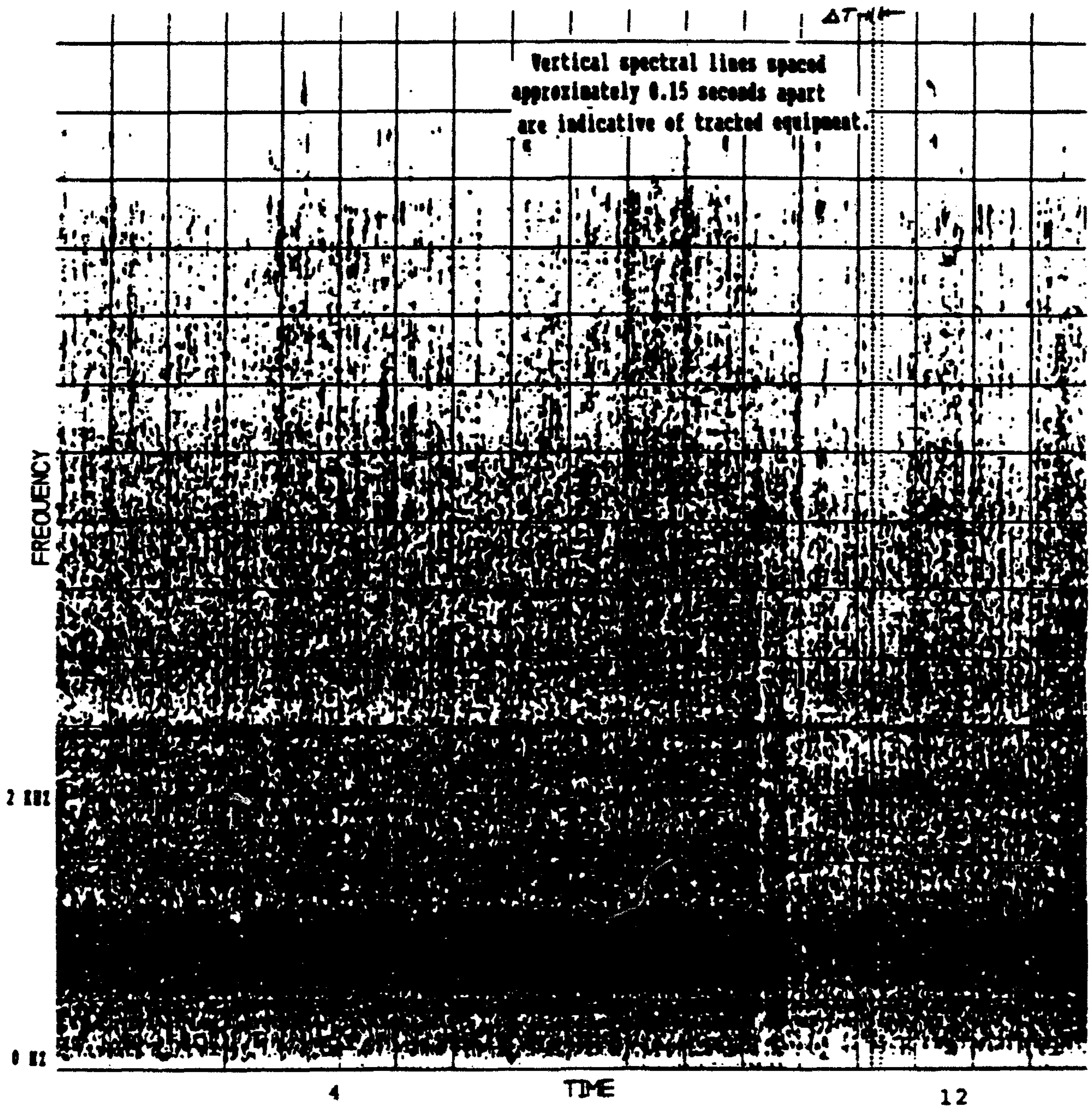

FIGURE C.8: DC - 8 khz Spectrograph Representative of CAT D8N Bulldozer

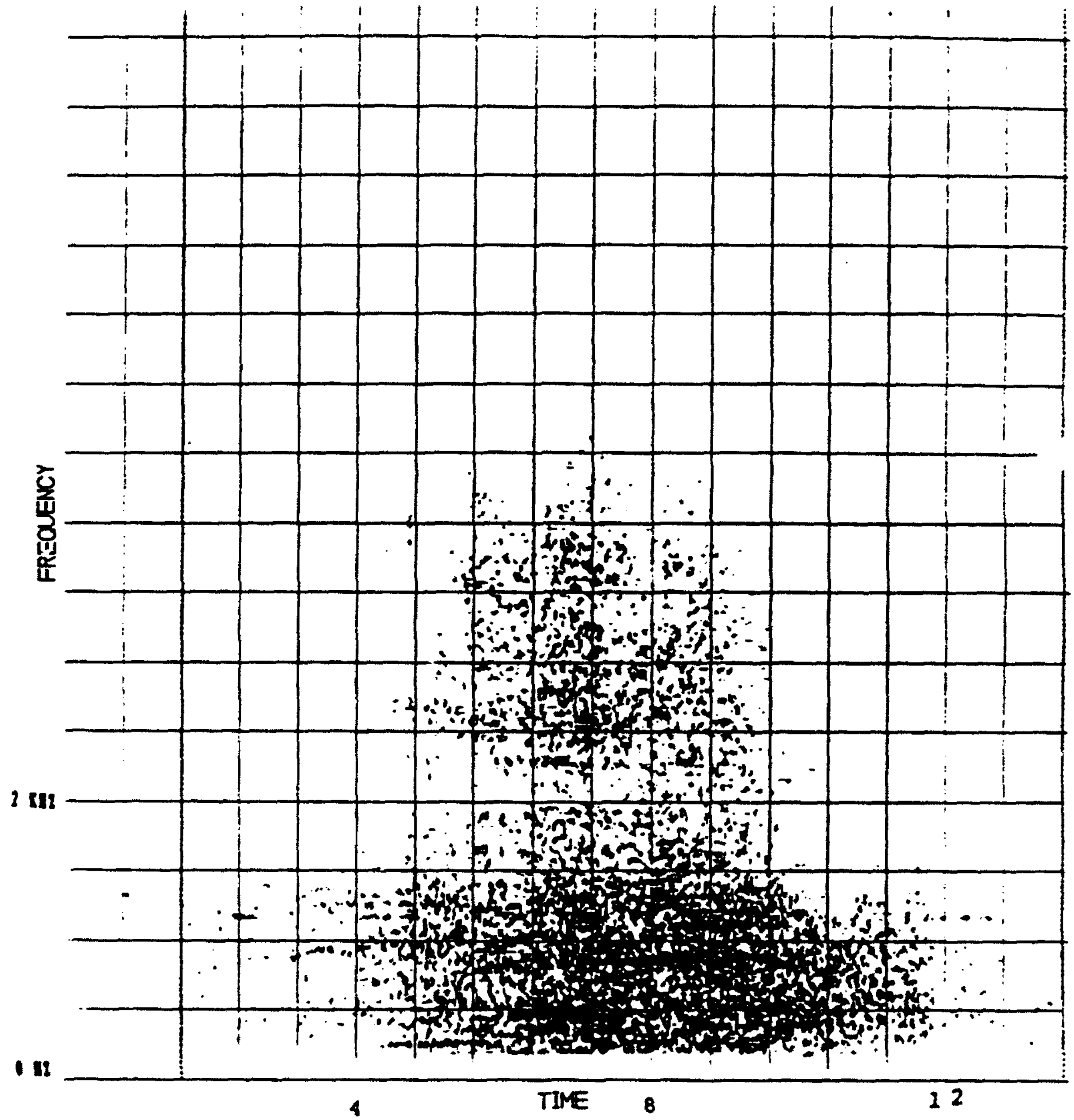

FIGURE C.9: DC - 8 khz Spectrograph Representative of Ford F-150 Pick-up Truck

Appendix D.
0 - 16 khz SPECTROGRAPHIC PROFILE

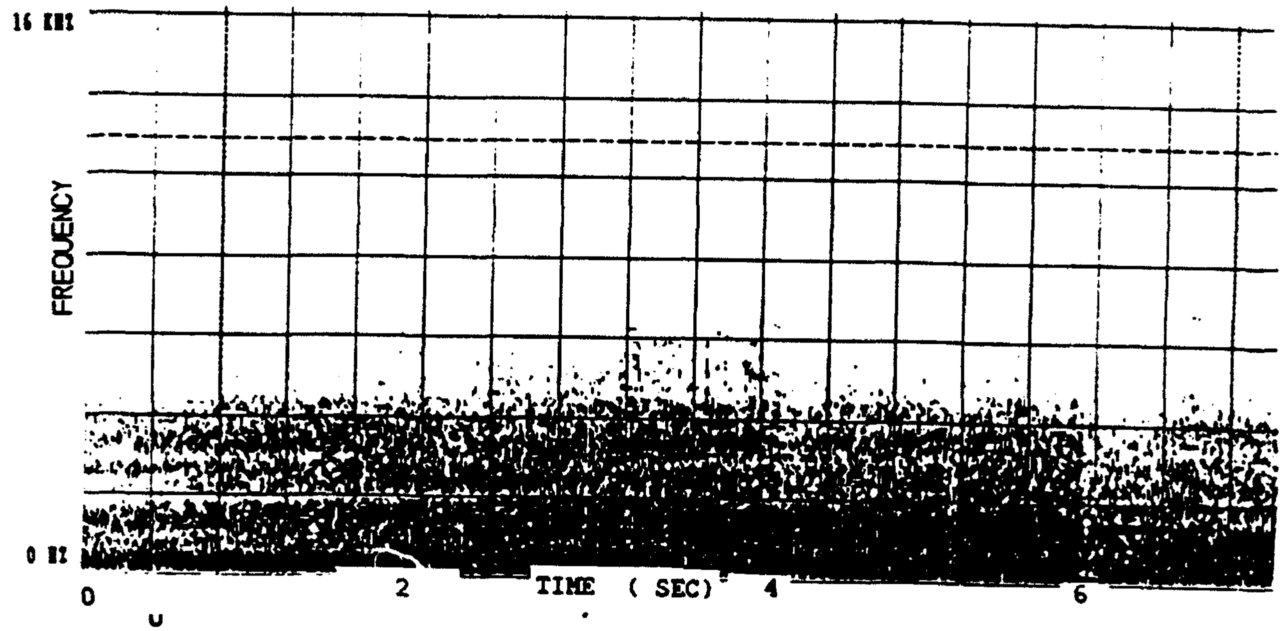

FIGURE D.1: DC - 16 khz Spectrograph Representative of Loaded CAT Scraper

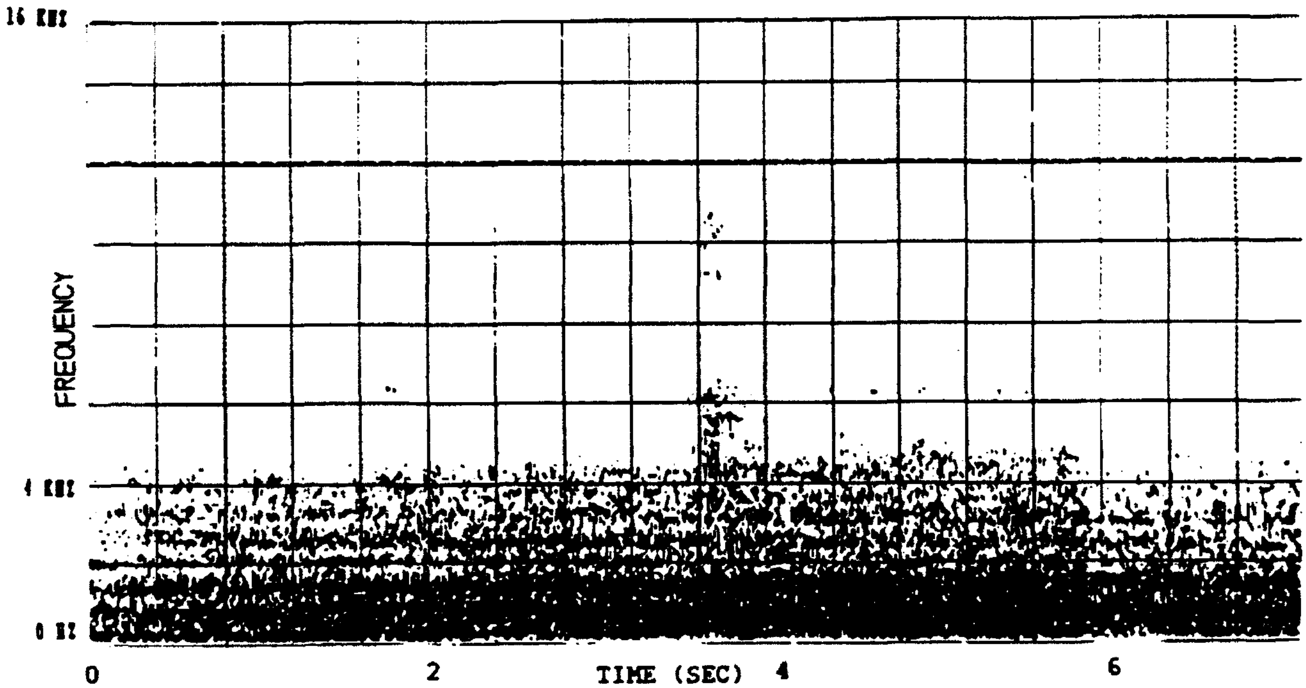

FIGURE D.2: DC - 16 khz Spectrograph Representative of Empty CAT Scraper

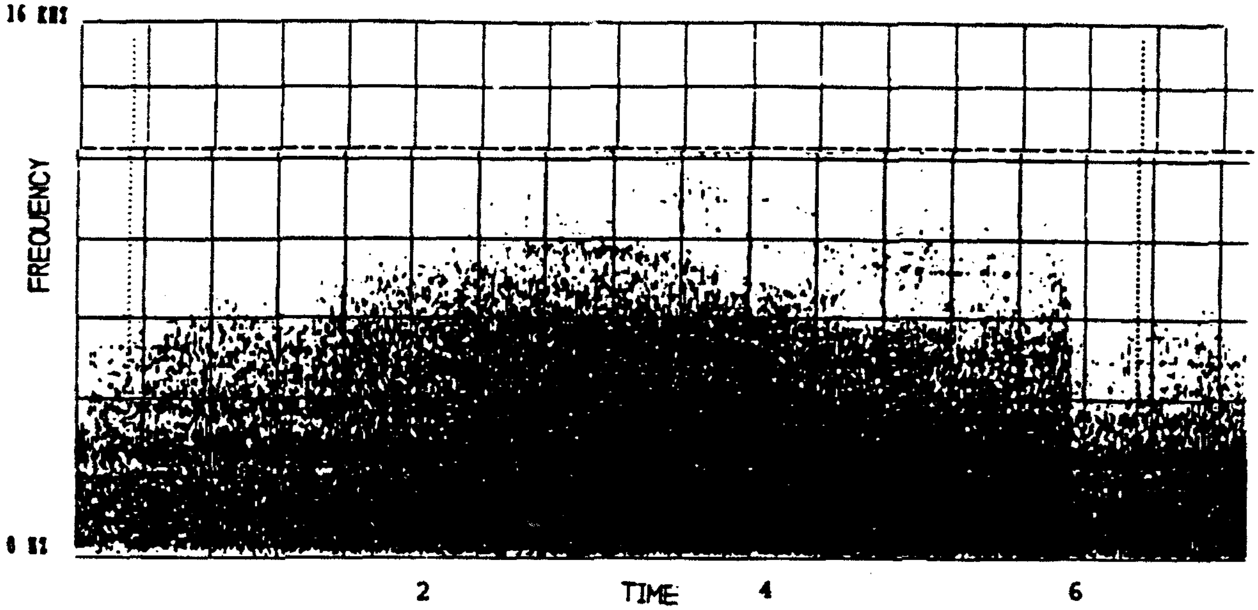

FIGURE D.3: DC - 16 khz Spectrograph Representative of Loaded 50 Ton Euclid Dump Truck

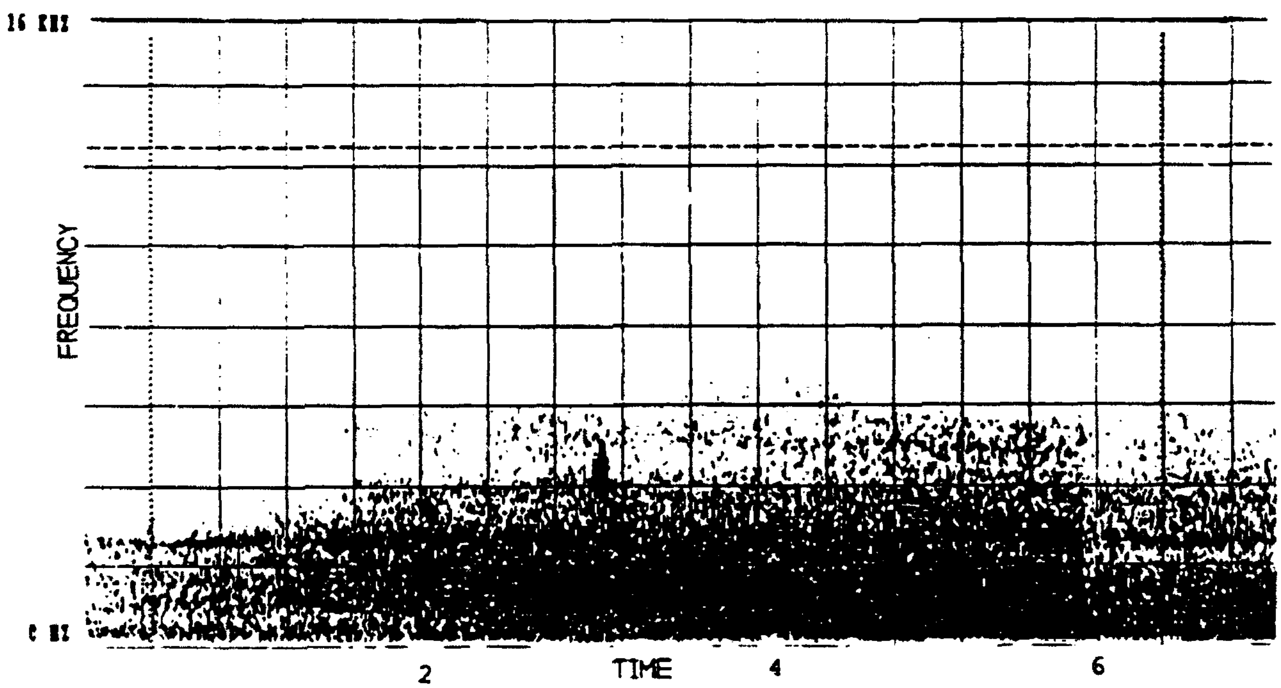

FIGURE D.4: DC - 16 khz Spectrograph Representative of Empty 50 Ton Euclid Dump Truck .

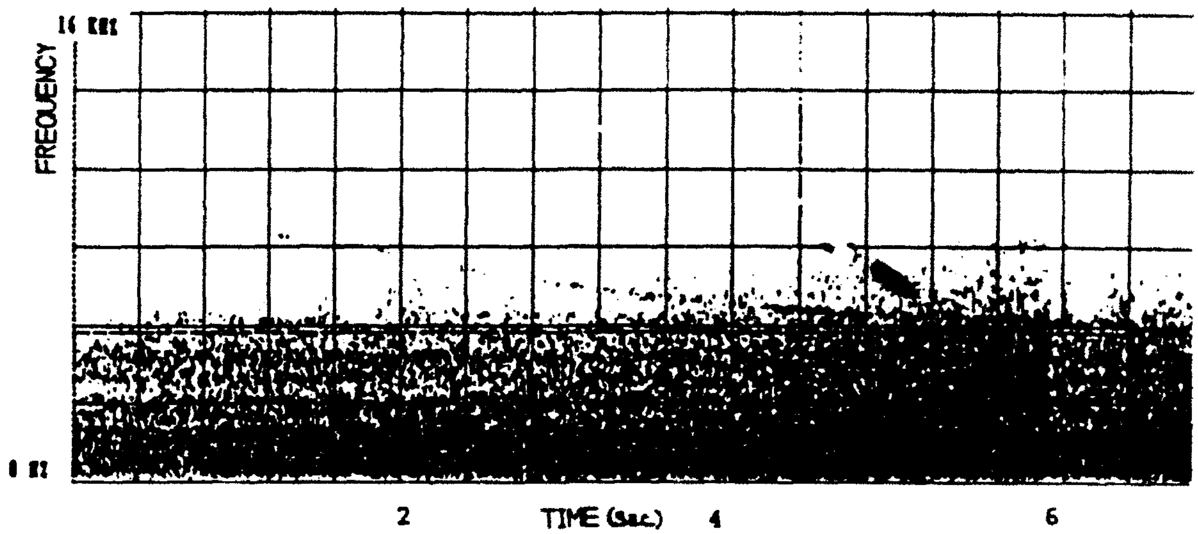

FIGURE D.5: DC - 16 khz Spectrograph Representative of Loaded 75 Ton Euclid Dump Truck

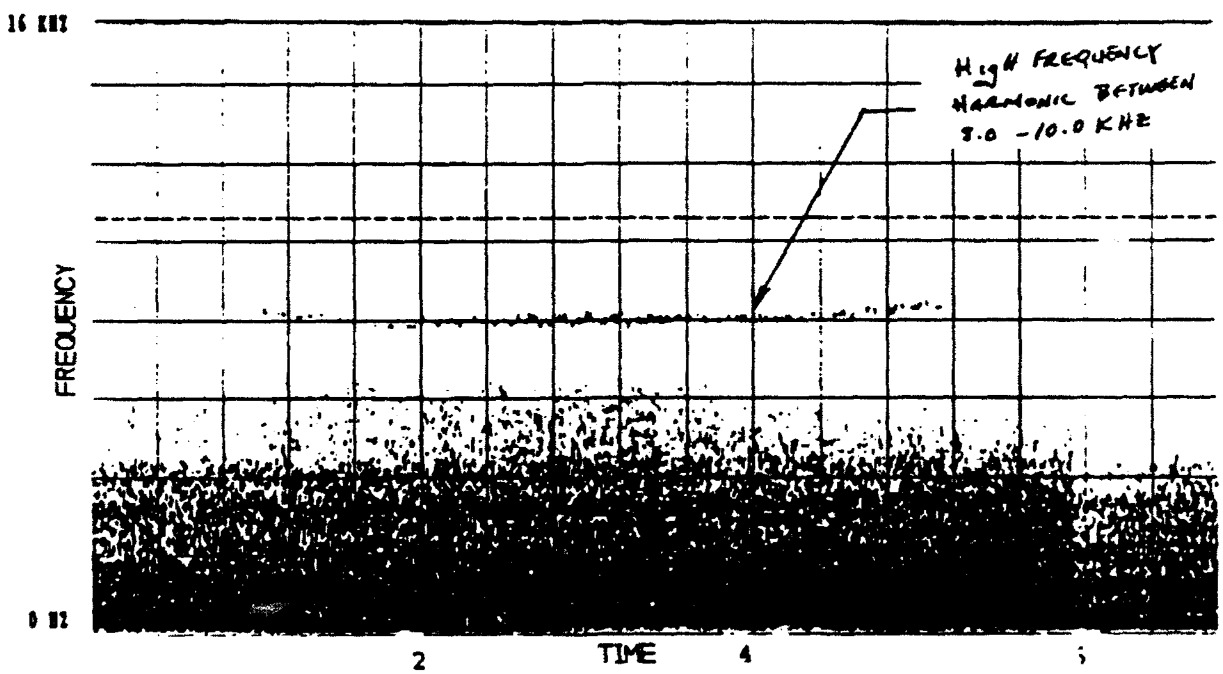

FIGURE D.6: DC - 16 khz Spectrograph Representative of Empty 75 Ton Euclid Dump Truck

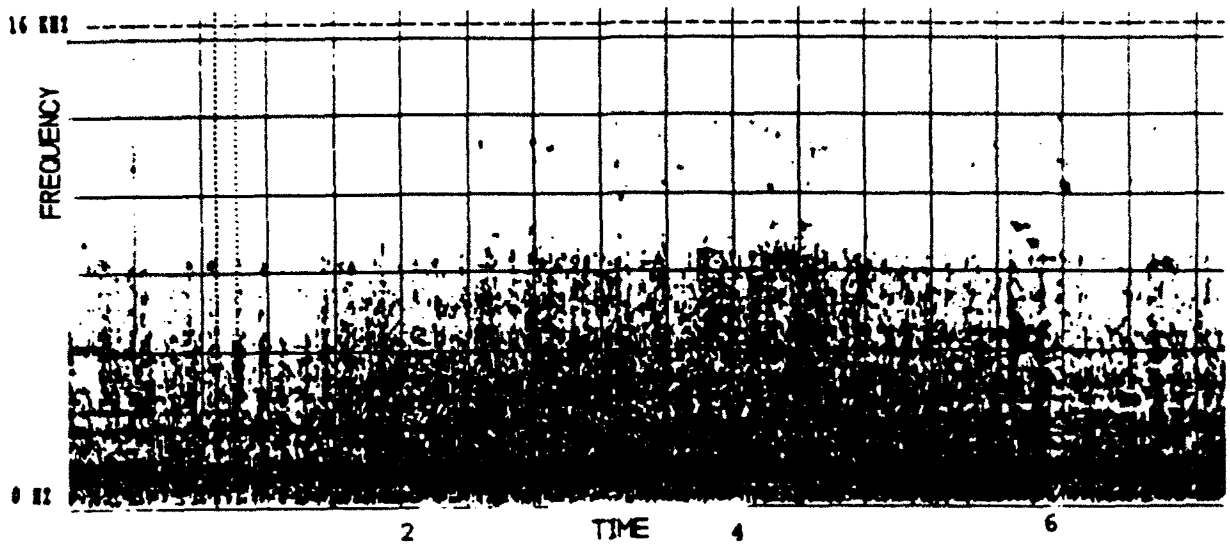

FIGURE D.7: DC - 16 khz Spectrograph Representative of Mack 6200 Gallon Water Truck

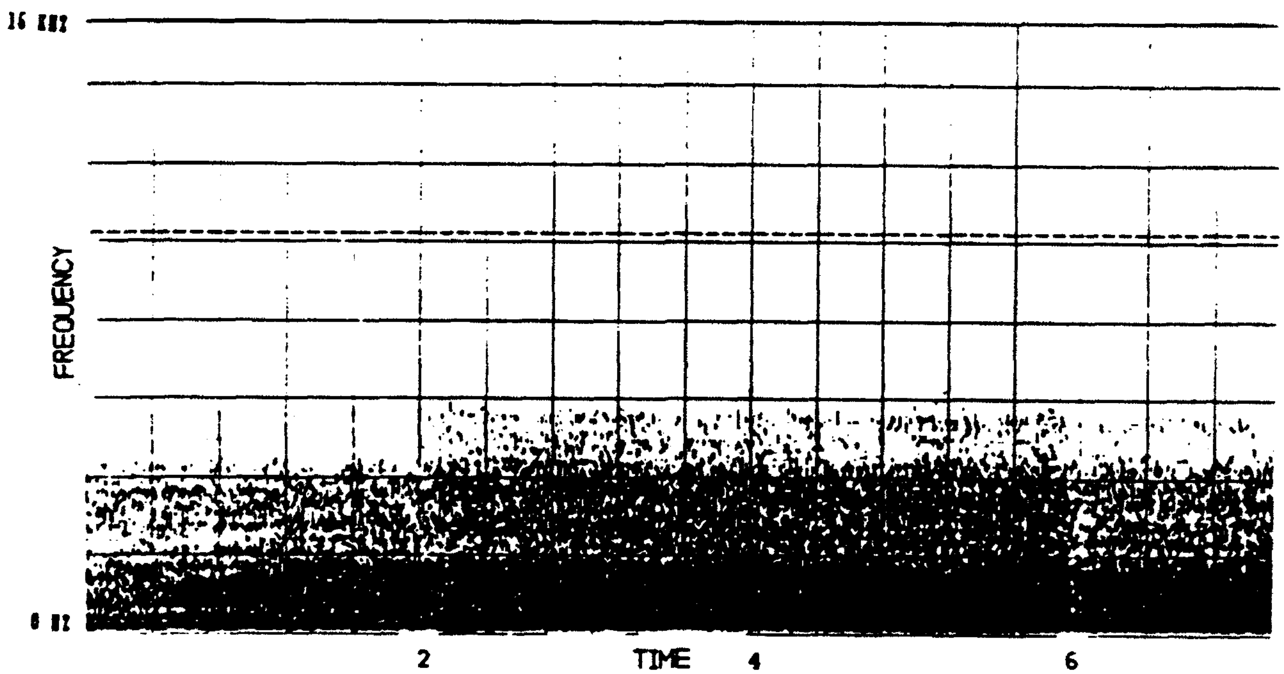

FIGURE D.8: DC - 16 khz Spectrograph Representative of CAT D8N Bulldozer

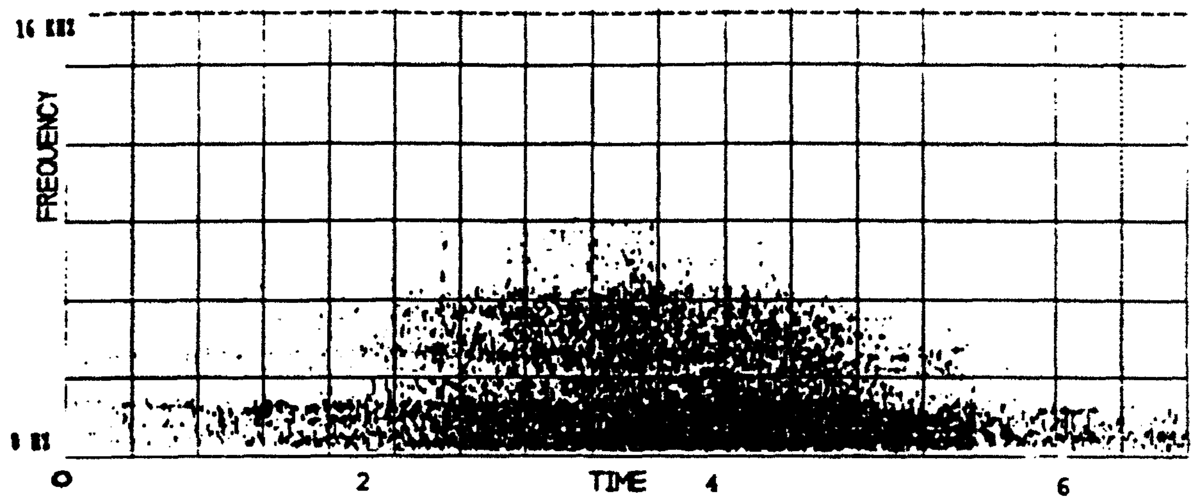

FIGURE D.9: DC - 16 khz Spectrograph Representative of Ford F-150 Pick-up Truck